# Principles of Operation

**System Overview** Figure 4 shows a block diagram of an XT100 system. The repair process begins when the operator loads a mask carrier (also known as an RSP, or Reticle SMIF Pod) into the load port module. The operator initiates the automated sample loading process by clicking the Load button on the Load/Unload dialog box in the software user interface.

A robotic system transfers the mask from the load port module to the loadlock at the front of the work chamber. Next, the loadlock door closes, and the loadlock is pumped down to low pressure so as not to introduce abnormally high pressures in the workchamber. After the loadlock is pumped down, the mask is transferred (via another robotic transfer system) to the mask holder on the sample positioning stage. An automated clamping/positioning system on the mask holder aligns the mask, and the mask is then ready to be positioned for imaging and repair procedures.

The XT100 system is comprised of several subsystems, each of which has its own software subsystem, power connections, communications node, and hardware controller. The hardware and cabling for these subsystems are mounted in racks in the left and right electronic cabinets, and are normally not accessible to the system operator. Figure 5 shows a top view of the major system components. Figure 6 and figure 7 show the location of the modules in the right and left electronics cabinets.

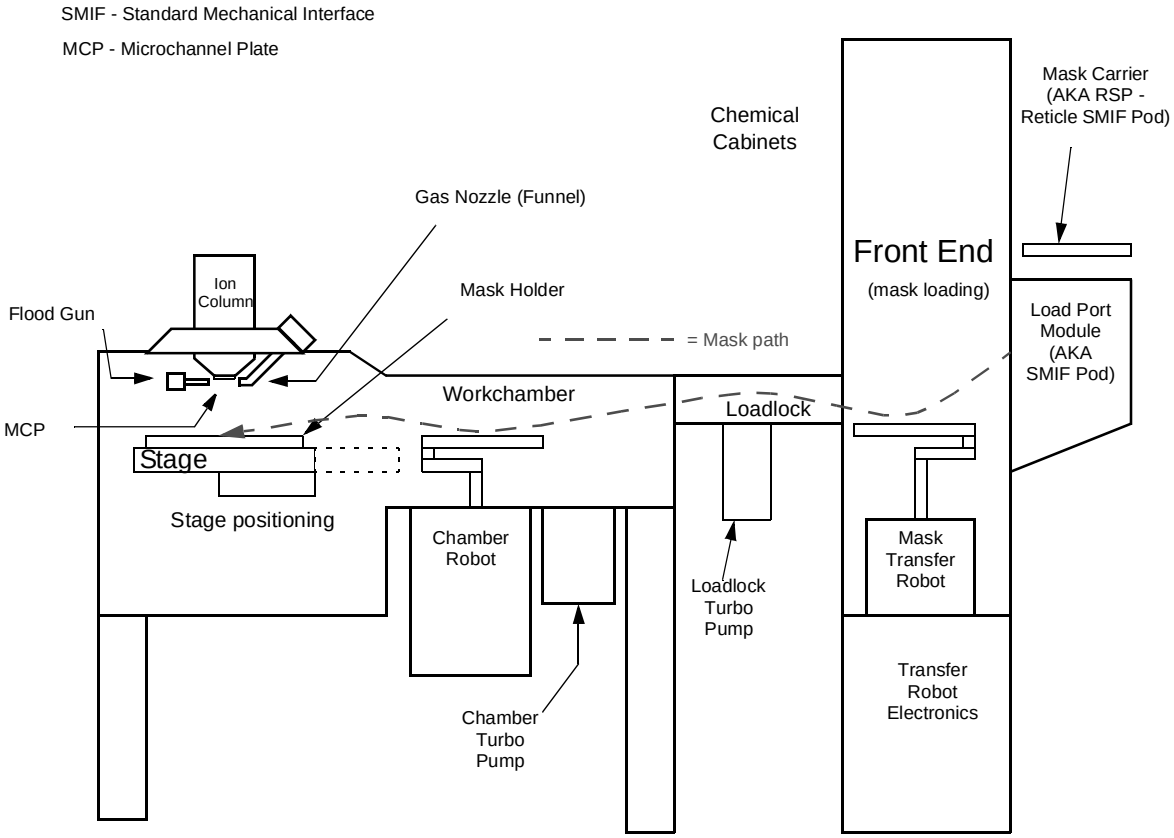


**Figure 4. System Block Diagram -- side view**

The system computer is a workstation running Microsoft's Windows NT operating system. The application program presents a graphical user interface (GUI) on the monitor, interprets input from the mouse, the knob panel, and the keyboard, and issues the appropriate hardware commands -- via a local area network -- to the various hardware control interfaces located in the electronics modules. See "Software Architecture" below for related information

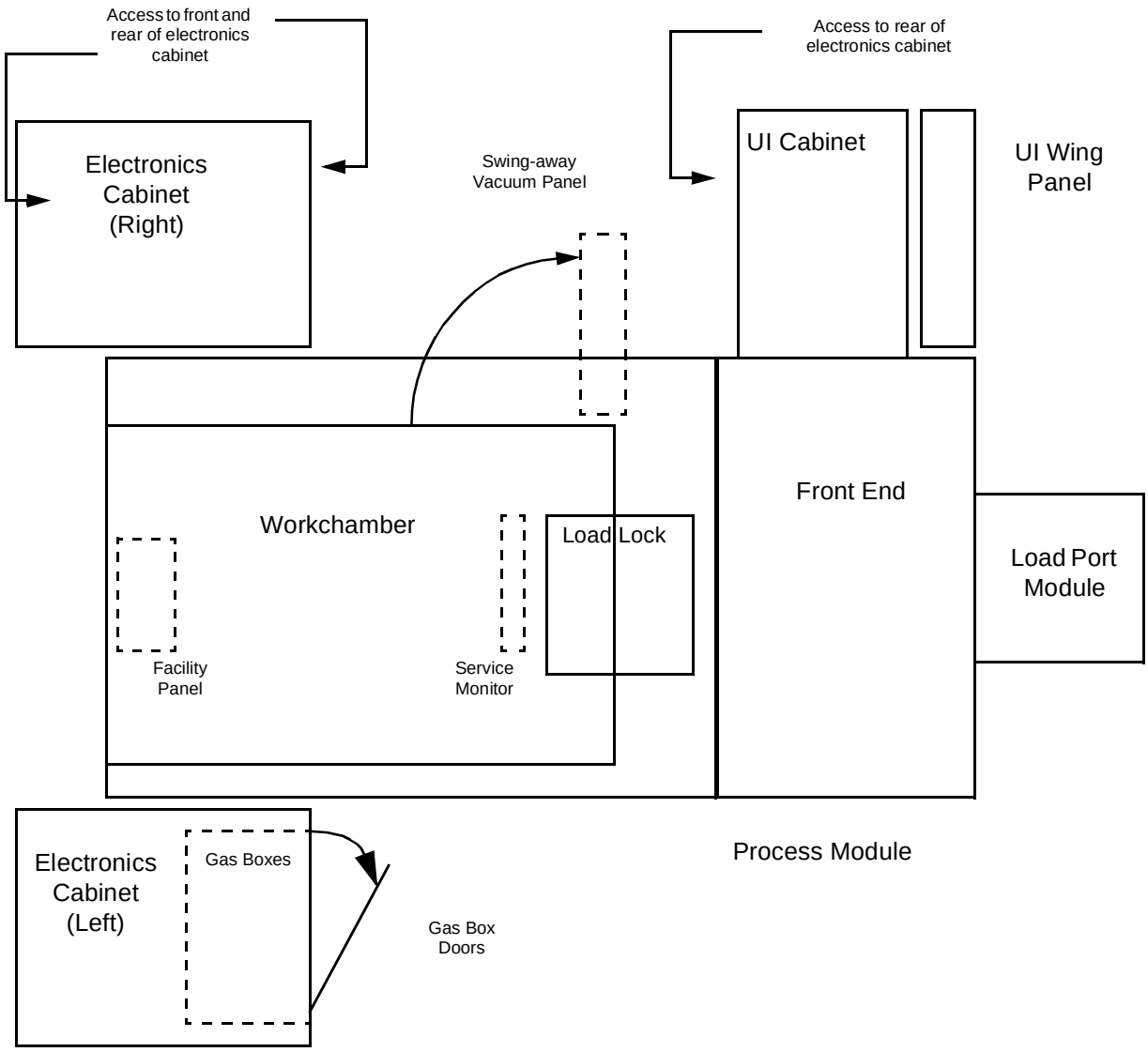


**Figure 5. Electronic Packaging: Top View**

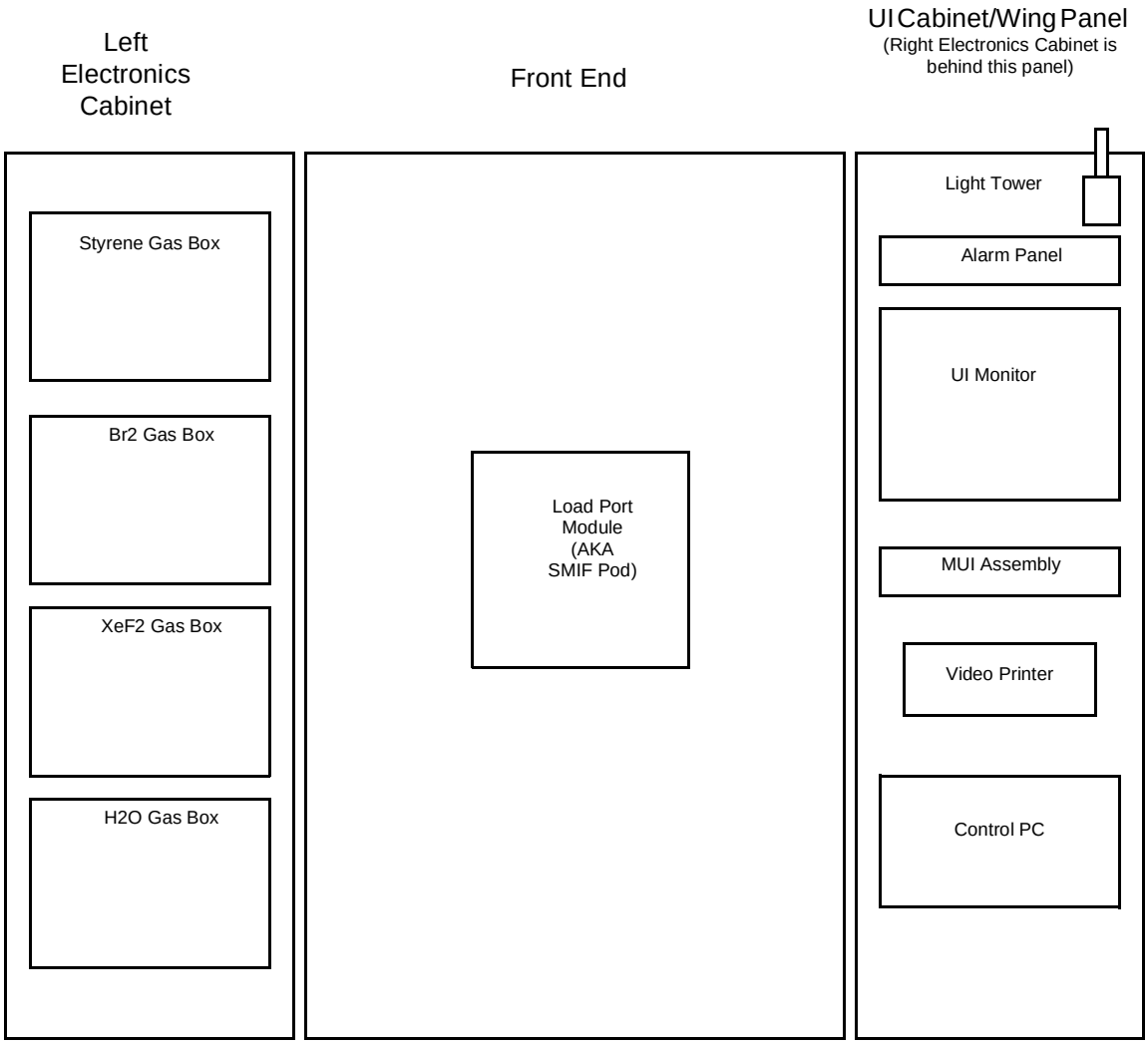


**Figure 6. Electronic Packaging: Front View**

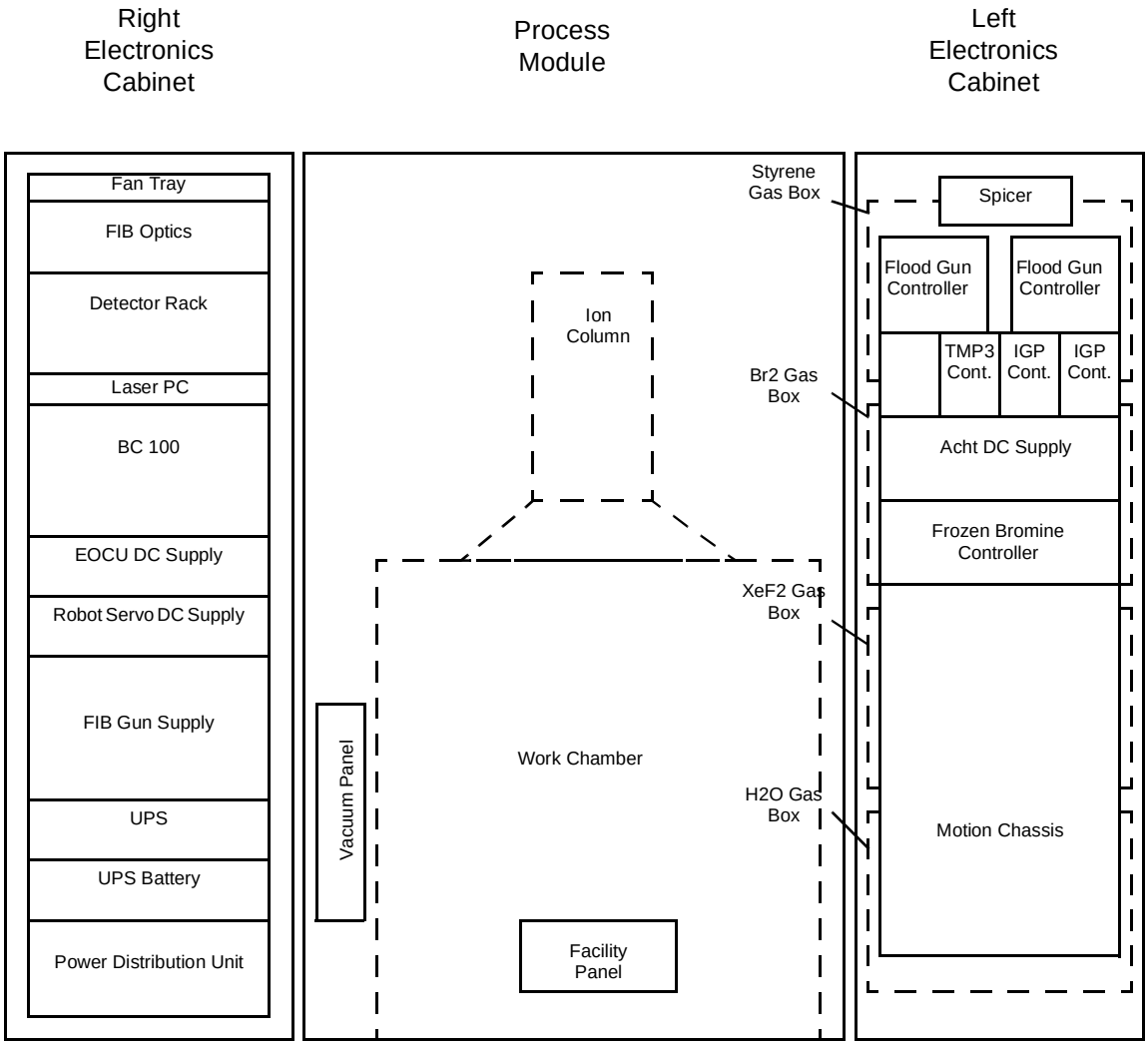


**Figure 7. Electronic Packaging: Rear View**

The knobs and switches on the knob panel communicate with the computer via the XT100 local area network. The software determines the states of the various knobs and switches by interrogating the knob panel interface. The alphanumeric keyboard is connected directly to the computer in the conventional manner.

**Software Architecture** Figure 8 is a conceptual diagram of the layered structure of the FIB system software. Commands pass downward from the user to the FIB system hardware, and status information passes upward from the hardware to the user.

**The Operating System** The foundation for the entire software system is Microsoft's Windows NT operating system. The operating system is a collection of software that controls the basic operation of the computer and that allows the execution of application programs by allocating memory space, passing information to and from hardware devices, and performing other related tasks. As an operating system, Windows NT includes *device driver* programs for operating the standard peripheral devices with which the computer is supplied (disk units, communications ports, and so forth). In addition to these device drivers, the FIB system manufacturer augments the operating system with device drivers for moving information to and from the special hardware interfaces, such as the vacuum controller, that are unique to the FIB system.

**The Application Program** At the top of the software structure is the application program, whose primary function is to present the graphical user interface (GUI) through which the user operates the system. Refer to the *XT100 Program Reference Manual* (part number 800-0000XX) for a description of that program.

**Software Design Principles** The XT100 software architecture is designed to be extendible, upgradeable, and easy to maintain. It consists of reusable software components so that changes can be made without recompiling the entire application and system-level code.

To ensure reusability, the software source code is written using C++, and is COM compliant. A brief explanation of C++ and COM follows.

**C++** C++ is an object-oriented programming (OOP) language that is organized around "objects" rather than "actions," and data rather than logic. Historically, a program has been viewed as a logical procedure that takes input data, processes it, and produces output data. The programming challenge was seen as how to write the logic, not how to define the data. Object-oriented programming takes the view that the objects that are manipulated are just as important as the logic required to manipulate them. Examples of objects range from human beings (described by name, address, etc.) to buildings and floors (whose properties can be described and managed) down to the little widgets on the computer desktop (such as buttons and scroll bars).

The first step in OOP is to identify all the objects to be manipulated and how they relate to each other, an exercise often known as data modeling. After an object has been identified, it can be generalized it as a class of objects, and defined by the kind of data it contains and any logic sequences that can manipulate it. Each distinct logic sequence is known as a "method." A real instance of a class is called an "object" or, in some environments, an "instance of a class." The object or class instance is what runs in the computer. The methods of each instance provide computer instructions, and the class object characteristics provide relevant data. The user can communicate with objects - and they can communicate with each other - via well-defined interfaces called "messages."

The concepts and rules used in object-oriented programming provide these important benefits:

- The concept of a data class makes it possible to define subclasses of data objects that share some or all of the main class characteristics. This property of OOP -- known as “inheritance” -- forces a more thorough data analysis, reduces development time, and ensures more accurate coding.

- Since a class defines only the data it needs to be concerned with, when an instance of that class (an object) is run, the code will not be able to accidentally access other program data. This characteristic of data hiding provides greater system security and avoids unintended data corruption.

- The definition of a class is reusable not only by the program for which it is initially created, but also by other object-oriented programs (and, for this reason, can be more easily distributed for use in networks).

- The concept of data classes allows a programmer to create any new data type that is not already defined in the language itself.

**COM** Microsoft’s Component Object Model (COM) is a way for software components to communicate with each other. COM is a binary and network standard that allows any two components to communicate regardless of what machine they're running on (as long as the machines are connected), what operating systems the machines are running (as long as it supports COM), and what language the components are written in.

A “component” is a building block program that is self-describing. This means that it can be run with a mix of other components and each will be able to understand the capabilities and characteristics of the other components. Practically, this means that a new application can be built by reusing components already known to exist, and without having to compile the application. It also makes it relatively easy to distribute different components of an application among different computers in a network. Microsoft's Distributed Component Object Model (DCOM) adds interfaces to do this.

In addition to its self-description, a component consists of one or more classes that describe objects and the methods or actions that can be performed on an object. A class (or co-class in COM+ terminology) has properties described in an interface (or co-interface). The class and its interface are language-neutral.

Associated with the class are one or more methods and fields that are implemented in a specific language (such as C++ or Java), or in a visual programming environment. When a class is instantiated, an object (something real that can be executed in the computer) is created. Sometimes the term “class” is also used for the instantiated object.

Using COM, objects (or classes) and their methods, as well as associated data, are compiled into binary executable modules. These executables take the form of files with a dynamic link library (DLL) or EXE file name suffix. A module can contain more than one class.

**DLL** A DLL is a Dynamic Linked Library - a subprogram initiated by the main program only when needed to perform a specific task, thereby saving space in memory. For example, as long as a user of Microsoft Word is editing a document, the printer DLL file does not need to be loaded into RAM (Random Access Memory). If the user decides to print the document, the Word application causes the printer DLL file to be loaded and run. DLL files that support the operation of specific devices are known as device drivers.

A DLL file is often given a ".dll" file name suffix. DLL files are dynamically linked with the program that uses them during program execution, rather than being compiled with the main program. The set of such files (or the DLL) is somewhat comparable to the library routines provided with programming languages such as C and C++.

**User Interface** At the top of the software structure is the graphical user interface (GUI) through which the user operates the system. The UI layer consists of an EXE framework, page controls, and managers (UI layer managers). Refer to the *XT100 Program Reference Manual* (part number 800-0000XX) for a description of that program.

**The Application Server** The objects within the application server provide an interface between the UI and the hardware server. These objects in this server are built using MS COM, and are designed to be very generic in the functionality they expose. For example, the Image Analysis component is designed to expose only generic image analysis functionality, with no XT100 contextual information. The application server contains the following objects:

- Recipe Page Manager
- Coordinate Lock Manager
- Defect Filter Manager
- Image Analysis Manager
- Repair Page Manager
- Chamber Schematic Manager
- Manual Navigation Manager
- MUI Controller
- User Access Manager

**The Object Model Layer** The Object Model Layer serves as the interface between the application server and the hardware server. It consists of objects that are implemented as COM components.

**The Hardware Server** [The hardware server consists of programs that run more or less autonomously to maintain continuous control of certain major FIB subsystems. The hardware server also provides the interface with the XT100 hardware. It consists of the following three layers:

BHV - Behavior layer to control interfaces between subsystems.

·MDL - Model layer to control subsystem behavior;

HAL - Hardware abstraction level to communicate with controllers and actuators (brain and brain and brawn boards) at each network node (CAN or Ethernet).

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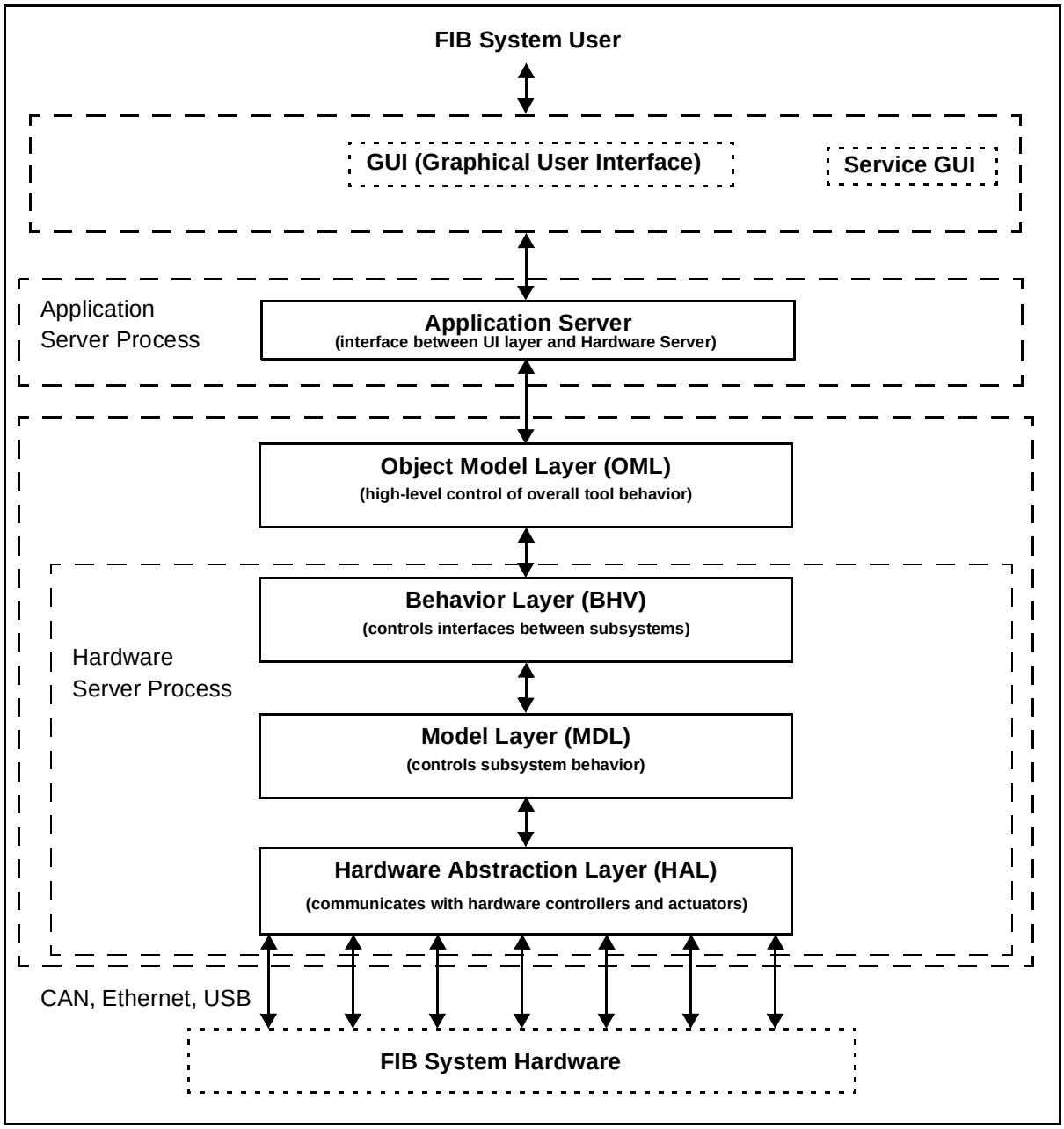



**Figure 8. Software System Organization**

All the objects within the hardware server are implemented as “bricks.” Bricks control distinct software subsystems (programs) within the XT100. These subsystems control specific hardware components. The behavior layer within the hardware server manages the interaction of the different subsystems.

A Brick is a Microsoft COM (Component Object Model) component implemented as a DLL. A DLL is a Dynamic Linked Library - a subprogram initiated by the main program only when needed to perform a specific task, thereby saving space in memory. A group of Bricks is managed by a "BrickBox," and each BrickBox runs in a separate Windows NT process. The configuration of the distribution of Bricks over BrickBoxes is stored in the Windows NT registry.

The servers accept requests from the application program on behalf of the system user, and operate the hardware by issuing the appropriate commands to the device drivers. Each server is responsible for a particular subsystem. For example, the *vacuum server* communicates with the *vacuum controller*—the hardware unit that operates the loading/unloading mechanisms and all of the pumps, valves, and gauges that are involved in maintaining high vacuum in the workchamber. When the FIB system user commands the application program to transport a mask holder from the loadport module, through the air lock chamber known as the *loadlock,* and onto the moveable stage in the workchamber (an event referred to as *loading*), the program sends a load request to the vacuum server, which sends the appropriate sequence of commands to the vacuum controller to evacuate the loadlock, to operate the transport mechanism, and to otherwise carry out the loading event. Other servers include the *positioning server*, the *HV (high-voltage) server,* which handles requests for setting the outputs of the high voltage power supplies and otherwise governs the operation of the ion column, and the *MUI server,* which monitors the positions of the knobs and switches on the manual user interface (also referred to as the knob panel). Refer to page 78 for more information about the servers.

**Control and Communications** The 100nm XT tool uses a distributed controls architecture that consists of internal CAN (Controller Area Network) and Ethernet networks. These local networks are configured in a "star" topology with each station (or "node") connected to a central hub, thereby reducing system cabling. Each major electrical subsystem resides on its own CAN or Ethernet node, and each node has a dedicated processor that allows local decision making to take place. Because the electrical subsystems are logically isolated from one another, each subsystem can be upgraded without disrupting the entire system.

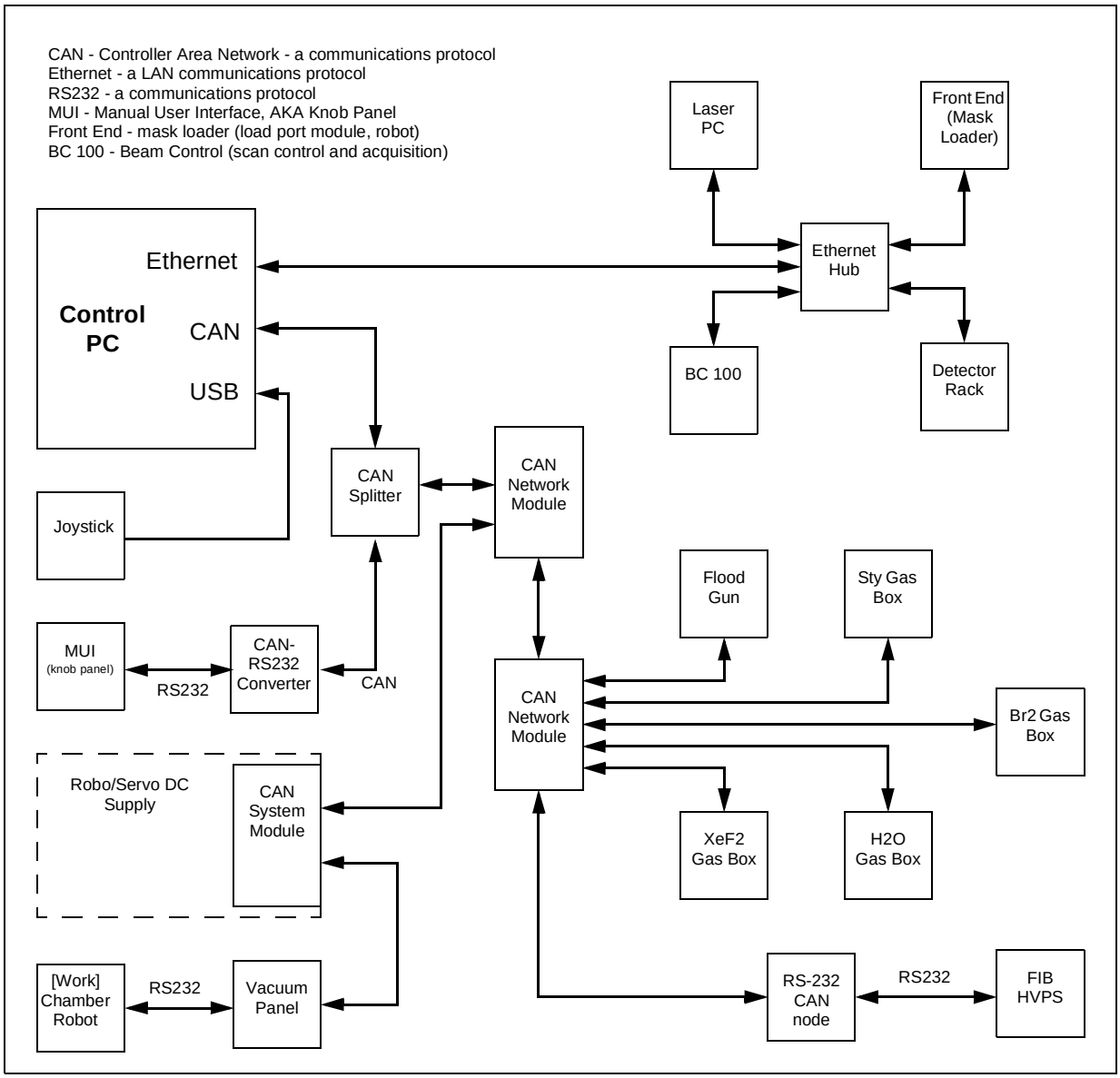



**Figure 9. Communications**

**The Controller Area Network** The majority of the electrical subsystems of the XT100 communicate via a CAN (Controller Area Network).

CAN is based on the so-called broadcast communication mechanism. This broadcast communication uses a message-oriented transmission protocol. It does not define stations and station addresses, it only defines messages. Each message is identified with a message identifier. A message identifier has to be unique within the entire network, and it defines not only the content, but also the priority of the message. This priority is important when several stations are competing

for bus access. The message with the lowest node ID wins bus access; in the XT100, the PC has the lowest node ID. Losing nodes keep trying until the bus is available.

A high degree of system and configuration flexibility is achieved as a result of this content-oriented addressing scheme. It is very easy to add stations to a existing CAN network without making any hardware or software modifications to the existing stations (as long as the new stations are receivers). This concept of modular electronics allows multiple reception, as well as the synchronization of distributed processes. Data required by several stations can be transmitted via the network, making it unnecessary for each station to know who sent the data. This concept makes it easier to service or upgrade the network, since data transmission is not based on the availability of specific types of stations.

**Ethernet** The remaining electrical subsystems of the XT100 communicate via an Ethernet-based LAN (local area network).

The XT100 uses a 10Base-T Ethernet, which provides transmission speeds up to 10 Mbps (Megabytes per second). The Ethernet LAN bus is configured in a “star” topology, with each station (or “node”) connected to a central multi-port repeater (also known as a hub). All connections in the network are point-to-point links implemented with unshielded twisted pair (UTP) cables.

Each Ethernet station competes for bus access using the Carrier Sense Multiple Access with Collision Detection (CSMA/CD) protocol.

The CSMA/CD protocol was originally developed as a means by which two or more stations could share a common media (cabling type). Each Ethernet station determines for itself when it will be allowed to send a data frame. The CSMA/CD access rules are summarized by the protocol's acronym:

- Carrier Sense—Each station continuously listens for traffic on the medium to determine when gaps between data frame transmissions occur.

- Multiple Access—Stations can begin transmitting any time they detect that the network is quiet (there is no traffic).

- Collision Detect—If two or more stations in the same CSMA/CD network (collision domain) begin transmitting at approximately the same time, the bit streams from the transmitting stations will interfere (collide) with each other, and both transmissions will be unreadable. If that happens, each transmitting station must be capable of detecting that a collision has occurred before it has finished sending its frame. Each must stop transmitting as soon as it has detected the collision and then must wait a quasi-random length of time (determined by a “back-off” algorithm) before attempting to retransmit the data frame.

**USB** The Joystick -- which can be used for manual stage movement -- communicates with the system via the USB (Universal Serial Bus) port on the Windows NT workstation.

**The Ion Column** The VisION™ ion column generates the ion beam that does the work for which the FIB system is intended. All of the other system hardware and software serves either to create a suitable environment for the generation of the beam, or to provide a more or less convenient means by which it can be put to use. Column performance is generally given in terms of beam current and spot size. For the mask repair application, the column is operated such that it produces ion beam currents in the range of 5 to 100 picoamperes and spot sizes from 10 to 40 nanometers.

Figure 10 is a schematic diagram of the ion column. Although simplistically depicted in the schematic as two-dimensional shapes, most of the elements through which the ions pass are either hollow cylinders or disks with central orifices. The element stack is aligned so that the geometric centers of the elements are on a vertical axis called the *central axis*. Ideally, the stream of ions passing through the column assumes the shape of a long narrow cylinder whose longitudinal center corresponds to that central axis. The electrically-active elements that make up the column are operated *electrostatically* (by the application of relatively constant voltage), as opposed to *electromagnetically* (by the passage of current through them). Note the presence of the gate valve (VGI) that can be closed by the software to isolate the upper part of the column, including the ion source and the limiting aperture assembly, from the lower part of the column for servicing (see "Ion Gun Isolation Valve" on page 58 for related information).

**Ion Emission** An *ion* is an atom that has acquired a positive or negative electrical charge by virtue of losing or gaining electrons, an effect known as *ionization*. The FIB system uses liquid metal gallium as the ion source. In the ionization process, gallium atoms usually lose one electron, thus becoming *singly-charged positive ions*. Being *charged* particles, ions can be accelerated and directed along particular paths by electrostatic fields, and their relatively high mass (compared with that of subatomic particles) allows them to be used to produce the milling and deposition effects.

Located at the top of the ion column, the *ion source* has a needle-like tip coated with liquid metal gallium. A current-regulated power supply heats the source slightly in normal operation to maintain the liquidity of the gallium. It also allows the source to be heated to a higher-than-normal temperature when necessary to eliminate impurities and to otherwise condition it for emission.

The source is held at a very high positive potential relative to ground. This potential is called the *acceleration* voltage because, when the ions are extracted from the source, it is the force exerted by this difference in electrical potential that causes them to accelerate through the column to reach ground potential. The higher the acceleration voltage, the faster the ions are travelling as they exit the column, and the greater the energy they impart to the specimen. The high-voltage server normally brings the acceleration voltage gradually to 30 kV when requested by the application program to power-up the ion column.

*Ion emission* from the source occurs primarily because of the difference in electrical potential between the ion source and the nearby extractor electrode. The resultant force draws the liquid gallium downward into a characteristically pointed shape known as a *Taylor Cone*, the gallium atoms at the tip of the cone become excited such that they begin to lose electrons (thus becoming, by definition, *positive ions*) and, having assumed a positive charge are drawn from the source to the extractor. Thus, the extractor voltage is the main determinant of the rate of ion emission. The

high-voltage server attempts to use the lowest extractor voltage that provides a stable rate of emission.

Although the extractor voltage is the main determinant of ion emission, it is not the only one. Various phenomena conspire to cause the rate of ion emission to vary slightly over time. To correct for these

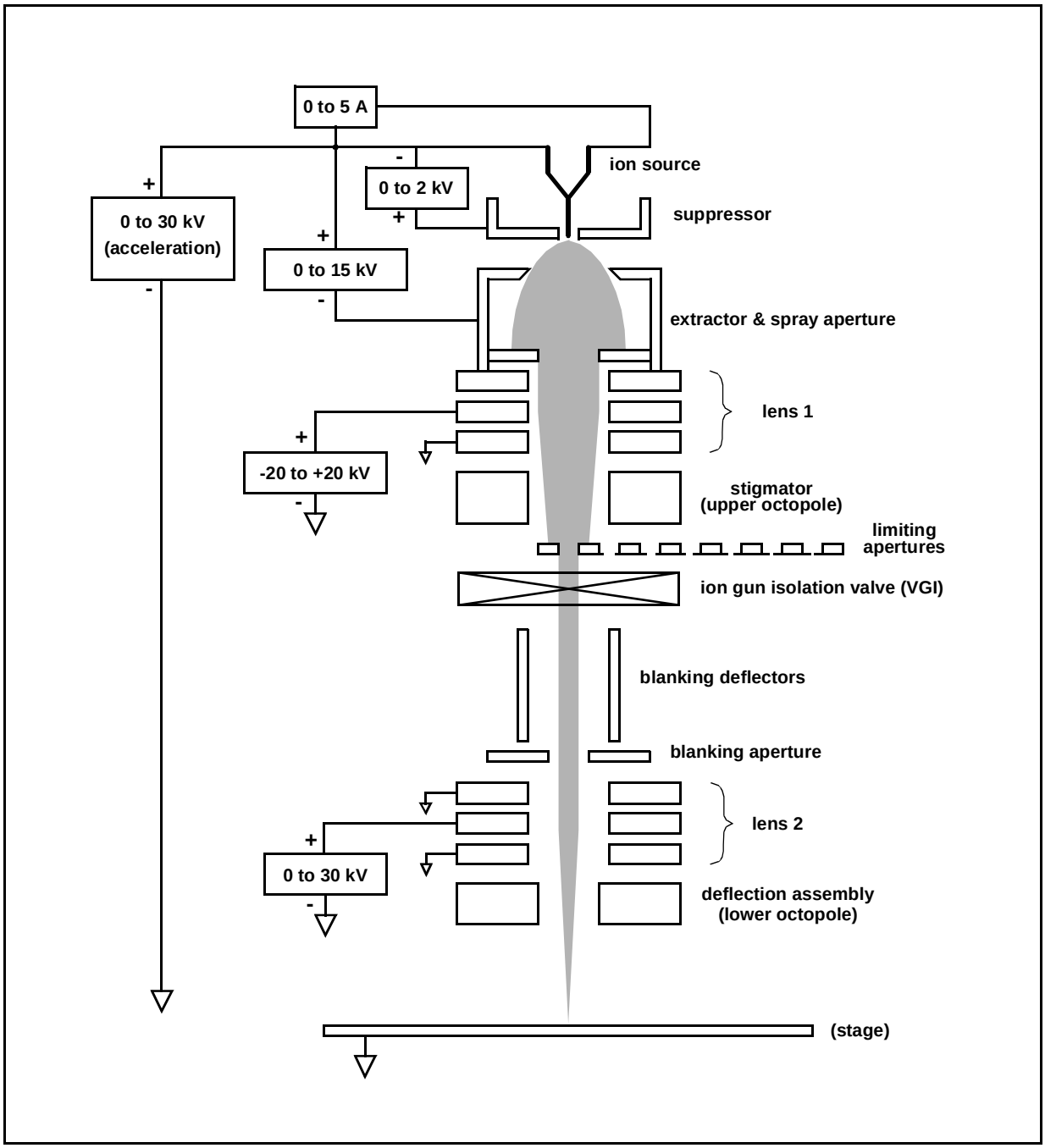



**Figure 10. Ion Column Architecture.**

variations in the interest of providing a constant beam current at the specimen, an element known as the *suppressor* is used. Because of its proximity to the source, a relatively small (and therefore easily controlled) positive potential on the suppressor counteracts the extraction voltage and thereby reduces the amount of emission.

The regulation technique then, is to set the extractor voltage for more emission than is required, and to hold the emission at a desired setpoint by dynamically adjusting the suppressor voltage. The HV server monitors the rate of ion emission and performs this regulation function automatically. The monitoring technique works as follows: Many of the ions that leave the source follow paths that do not take them through the annular orifice in the extractor (the spray aperture), but in fact land on and are absorbed by the extractor electrode and the metal surrounding the orifice in the spray aperture. Typically, the gallium ions are singly charged (deficient in one electron), and each ion absorbed by the extractor is neutralized by an electron supplied by the power supply that develops the extractor voltage. Thus, there is a correlation between the electron current flow in the extractor circuit—which is relatively easy to meter—and the rate of ion emission from the source. The current generated in the extractor circuit is known variously as the *extractor current* and the *extraction current*. The HV server program adjusts the suppressor voltage to maintain an extractor current setpoint, which is typically about 2 microamperes—high enough for a stable supply of ions that will provide the desired beam current for the work at hand, but low enough for reasonable source-life. A liquid gallium source operated at 3 microamperes can be expected to provide stable emission for at least 1000 hours.

A *spray aperture* is at the bottom of the extractor, and it allows only those ions that are travelling more or less parallel with, and close to, the central axis to pass. These ions collectively exhibit a relatively narrow energy spread (they are all travelling at about the same velocity), and therefore are more suitable for focusing by Lens 1.

**Lens 1** Lens 1 is a three-element structure in which each of the elements is operated at a different electrical potential. The electrostatic field gradients produced by the differences in potential causes the paths of the ions near the edges of the beam to bend inward toward the center, thereby making the beam convergent.

The uppermost element of Lens 1 is operated at the same potential as the extractor (which means that the magnitude of the extraction voltage changes the focusing effect of the lens), and the lowermost element of Lens 1 is grounded. Assuming that the extraction voltage remains constant, which is normally the case, it is the potential that is applied to the middle element of the lens that is increased or decreased to vary the focusing effect of the lens.

Lens 1 is used to set the beam current by determining the diameter of the beam as it arrives at the beam-limiting aperture element. If the diameter to which the lens focuses the beam is equal to or less than the diameter of the beam-limiting aperture, the current density—the number of ions per unit area that pass through the aperture—is maximum. If Lens 1 is used to defocus the beam so that its diameter exceeds the size of the aperture, the current density downstream from the aperture is diminished. Figure 11 illustrates the principle.

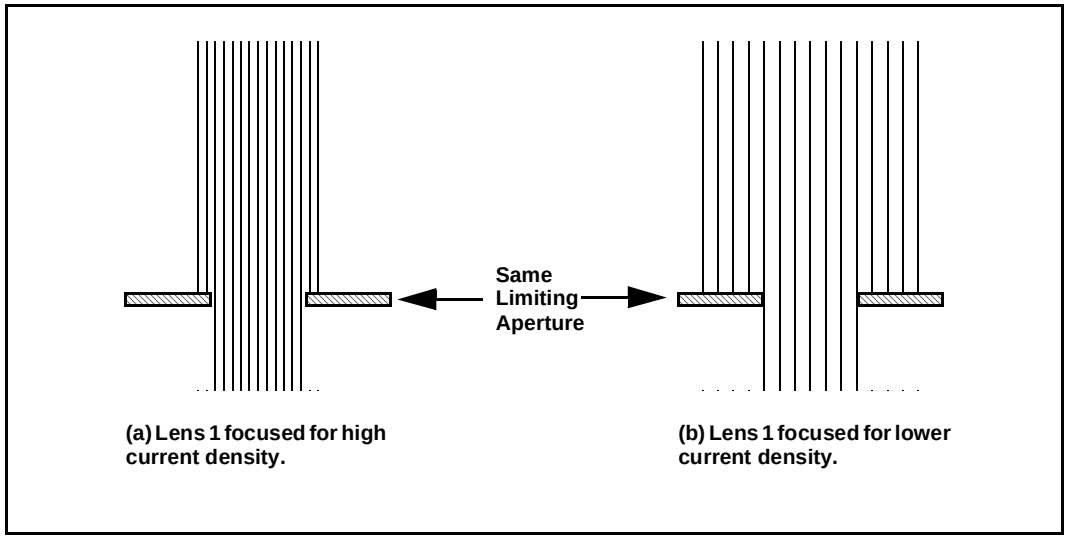



**Figure 11. The Effect of Lens 1 on Current Density.**

**Beam-Limiting Apertures** A *beam-limiting aperture* is any of 14 apertures that are arranged in two parallel lines on a horizontal sliding bar and that can be brought into position by a mechanical drive mechanism. Homing the positioning mechanism withdraws the sliding bar completely so that the beam is unrestricted; this is normally done only when servicing the column.

A beam-limiting aperture reduces the beam diameter at the point of interception, and has a proportional effect on the *spot size*—the smallest spot to which Lens 2 can focus the beam on the specimen. The combination of the size of the beam-limiting aperture and the current density established by the focusing of Lens 1 is the major determinant of beam current delivered by the column and, to a lesser degree, of spot size (the spot size increases somewhat with the current density).

The standard set of beam-limiting apertures installed on Accura 850 systems consists of six 25-μm, apertures, two 30-μm apertures, four 40-μm apertures, and two 60-μm apertures. The 25-μm aperture size is expected to be used most often because it yields a combination of spot size (20 to 30 nm) and beam current (10 to 20 pA) that is typically preferred for mask repair. An aperture eventually deteriorates with use—the orifice becomes enlarged by the ion beam; hence the need for redundancy. While the ion column remains powered up, the currently-selected beam-limiting aperture remains in the path of the beam and is eroded by it. To extend the useful life of the aperture set, a “sacrificial” aperture should be selected (“parked” in the beam path) if the ion column is to remain powered up but idle for any appreciable time. The sacrificial aperture would be one of the little-used apertures (e.g., 60-μm), or any aperture that has already deteriorated beyond use.

The Lens 1 focus voltage that produces the highest current density (irrespective of spot size), for each of the beam-limiting apertures is one of several items of data specified in a data structure called a *lens table,* and is asserted by the software when it positions a particular aperture for use. The amount of stigmation force that is required also tends to vary with the beam's diameter and current density, which means that selecting a beam-limiting aperture of a different size usually requires re-stigmating the beam. Therefore, the software also saves stigmation values in association with each of the beam-limiting apertures in the lens table. See "Stigmation" below.

When it is desirable to alter the current density or (to a much lesser degree) the spot size for a given beam-limiting aperture, a *virtual aperture* can be implemented through the application software. When the user selects a virtual aperture, a specified hardware aperture is selected, but the software sets the Lens 1 focus voltage according to an alternate lens table.

**Stigmation** The *upper octopole,* also known as the *stigmator,* is used to introduce correction for *astigmatism,* which is the failure of the column to make the ions converge uniformly to a circular spot. Astigmatism can be expected to develop as the beam enters Lens 1 because, despite the passively collimating effect of the spray aperture (see above), not all the ions entering the lens will be on parallel paths, nor will they be evenly distributed about the central axis. The focusing effect of the lens is therefore not uniformly applied, and the ions do not become uniformly convergent.

Figure 12 (a) attempts to illustrate the nature of the problem by representing the beam as having become elliptical in cross section (instead of circular) as it emerges from Lens 1, the result of having become more convergent in *y* than in *x*. Note that the dots representing the ion paths are not evenly distributed. Thus, the problem is not simply a matter of the cross-sectional shape of the beam being non-circular (which could be corrected by a limiting aperture), but involves the spacing of individual ion paths, and Lens 2 would be expected to amplify the effect.

The stigmator consists of eight radially-oriented electrostatic deflection elements. Voltages of equal magnitude and polarity are applied to opposite elements so as to produce opposing forces that tend to reshape and collimate the beam. Figure 12 (b) attempts to illustrate this effect, and Figure 12 (c) attempts to illustrate the result. The stigmator is used empirically to obtain the most sharply focused spot for the column as a whole, and its correction therefore represents some combination of undoing the astigmatic effect of Lens 1 and anticipating the astigmatic effect of Lens 2.

Minor differences in the forces exerted by a given voltage on opposite poles of the stigmator (due to manufacturing tolerances) are corrected by introducing voltage offsets through a service procedure known as the *quad balance calibration*.

Because the stigmator is located above the beam-limiting aperture, it can also used to deflect the beam slightly to center it on the aperture, an effect that is known variously as *fine align*, *upper shift*, and *beam align.*

**Blanking** Given the amount of electrical power that is required to produce ion emission, and the complexity of maintaining stable emission, the ion beam cannot be rapidly switched on and off at the source. Instead, the combination of the *blanking deflectors* and the *blanking aperture* is used to achieve this switching effect as follows.

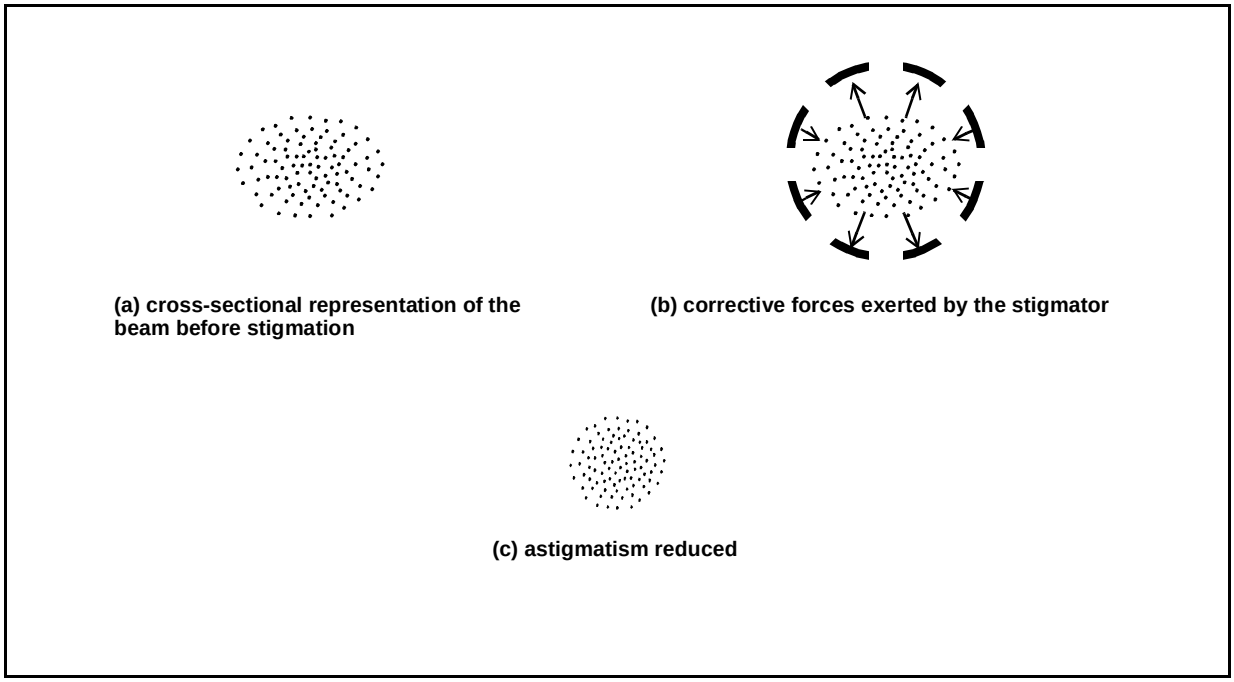

(a) cross-sectional representation of the beam before stigmation
(b) corrective forces exerted by the stigmator
(c) astigmatism reduced

**Figure 12. Stigmation.**

With no potential applied to the blanking deflectors, the beam passes undisturbed through a large orifice in the blanking aperture element. This is the *unblanked* state. When voltages of opposite polarities are applied to the blanking deflectors, the beam ions, being positively charged, are repelled by the positive deflector and attracted by the negative deflector, the net effect being that the beam misses the orifice and is absorbed by the aperture element. This effect is known as *blanking the beam*. When the column is powered up, but not in actual use, the beam is *blanked*.

The amount of beam current that the column is delivering to the mask is an important factor in the milling and deposition processes. The blanking aperture element provides one means of measuring the beam current in the column downstream from Lens 1 and the beam-limiting aperture. The blanking aperture element is connected to electrical ground through a DC metering circuit. While the beam is blanked, the potential created by the arrival of positive ions draws electron current from ground through this metering circuit. The beam current can also be measured with the ion faraday; see page 53.

When the beam is deflected onto the blanking aperture by the blanking elements, it does not instantaneously disappear—it moves out of the normal scan field and into occultation. Although its motion is very rapid, it still delivers a finite ion dose along the way. Depending upon the application, this may result in a cumulative effect known as *blanking tails*. See “Rastering” below for related information.

**Lens 2** Whereas Lens 1 is used to adjust the beam current density, Lens 2 is used to focus the beam on the specimen. This is the lens that the user controls with the Focus knob on the knob panel (or the software presets). Lens 2 applies the same principle as Lens 1 to cause the ions to converge as they travel toward the *focal plane*—the plane in which the ion trajectories cross and therefore the plane in which the spot size is smallest.

**The Deflection Assembly** The deflection assembly includes an octopole that is similar to the stigmator, but is operated differently. In the stigmator, opposing pairs of deflectors are used to exert lateral "push-push" or "pull-pull" forces on the beam as necessary to correct for astigmatism. Once the appropriate combination of correctional voltages is established, it can be maintained until some event that changes the beam's astigmatism occurs. In the deflection assembly, opposing pairs of deflectors are used dynamically to exert lateral "push-pull" forces to deflect the beam from the central axis. Thus, they work somewhat like the blanking deflectors except that, with four pairs of deflectors, the beam can be placed at any point within the range of deflection. Also, whereas the voltage applied to a blanking deflector is either zero or some predetermined fixed value, the voltages applied to a deflection assembly are scaled according to where the beam is to be placed. During imaging, milling, or deposition, the ion beam is deflected back and forth along a series of parallel paths in what is called a *raster pattern* (see "Rastering" below). To achieve this, various combinations of ramped voltages are applied to the deflection assembly to move the beam along the appropriate paths.

Typically, the area that a raster has to cover is smaller than the deflector's maximum scan range. When this is the case, the raster-producing scan signals that are applied to the deflector can be biased so that they offset the center of the raster from the center of the deflection range, an effect known as *panning*. The pan knobs on the knob panel allow the user to pan the scan field when imaging with small fields of view, and the application software also uses the panning effect to correct for stage-positioning error when it brings work sites on the mask under the ion column.

## Rastering

*Rastering* means scanning the beam such that it traces a pattern of closely-spaced parallel lines as shown in Figure 13. One iteration of this raster scanning pattern is called a *frame*. It is also referred to as a *raster* (refer to the Glossary for further discussion of *raster*). Each of the *scan lines* constituting the raster scanning pattern is in fact a linear array of discrete points to which the beam is rapidly deflected and at which it pauses or *dwells* for a predetermined period. These points are called *dwell points*, and the time for which the beam dwells at each dwell point is called the *dwell time*. The *dwell point spacing*, also called *DAC spacing*, is the distance between the centers of adjacent points.

Raster scanning is used for milling, deposition, and imaging. Two raster scanning schemes are implemented: *normal* and *serpentine*. In normal raster scanning, the beam proceeds along each scan line in the same direction. It is *blanked* (see page 41) at the end of each scan line while the deflection electronics are directed to place it at the opposite end of the next scan line. It is then unblanked, and deflection proceeds. Except for multiplex imaging rasters, the beam is not blanked between dwell points (multiplex imaging is explained under "Imaging Modes" on page 45). The act of redirecting the beam from the end of one scan line to the opposite end of the next scan line is called *retrace*. Serpentine scanning involves reversing the scan direction on alternate scan lines, thus eliminating retrace and the need to blank the beam while it is taking place. The normal raster

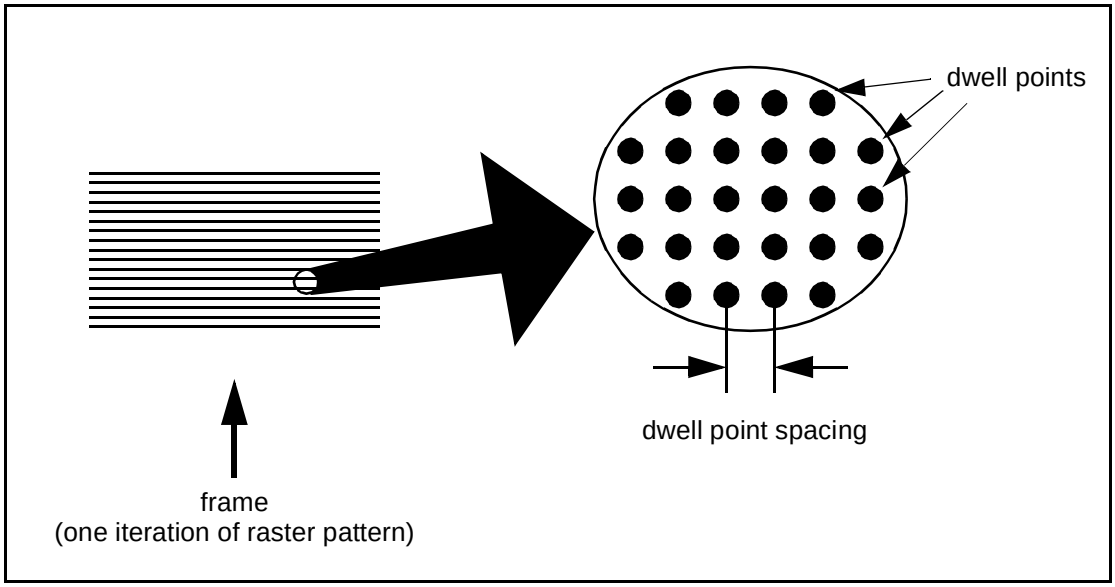



**Figure 13. Raster Scanning.**

scanning pattern described above is used for image acquisition, with one low-dose (short dwell time) frame producing each image.

To obtain the milling effect, many frames, each delivering a relatively high dose (long dwell time), are superimposed. To obtain deposition, thousands of low-dose frames are superimposed while the deposition chemical flows onto the specimen. When thousands of normally-rastered frames are superimposed in one location, the minute dosage that the beam delivers to the mask outside the raster as it is blanked (travels into occultation) at the end of each scan line has a cumulative effect. This results in spurious milling or deposition, an effect known in either case as *blanking tails*. For this reason, serpentine scanning is preferable whenever large numbers of frames are to be superimposed because it decreases the number of times the beam is blanked (by a factor equal to the number of frames times the number of scan lines per frame).

Regardless of which scanning mode is chosen, the beam is always blanked after the last scan line of each frame while it is being deflected back to the start of the first scan line of the next frame.

The total time between the end of one scan line and the beginning of the next is called the *retrace time*. This time consists of the actual deflection time and a programmable delay. The the entire cycle time between the start of one frame and the start of the next is known as the *refresh time*. Refresh time is necessary during deposition to allow the deposition gas to be replenished on the surface of the mask between frames.

**Ion Dose** The *ion dose* is the quantity of ions delivered to the mask per unit area, which translates to the depth of milling or the thickness of deposition.

The dose delivered for any particular operation is a function of the beam current, the dwell point spacing, the dwell time, and the number of frames (rasters). Dose does not take acceleration potential (which determines the velocity or *energy level* of the ions) into account, so the effect on the mask of a given dose is likely to be less, for example, with the acceleration potential at 25 kV than at 30 kV.

The units of dose are either nanocoulombs (of electrical charge) per square micron ($nC/\mu m^2$), or ions per square centimeter ($ions/cm^2$). One $nC/\mu m^2$ is equivalent to about $6.25 \times 10^{17}$ ions per square centimeter.

**FIB Imaging** The FIB system produces gray-scale images by applying the same principles used by scanning electron microscopes (SEMs). That is, the mask is probed by the ion beam in a raster scanning pattern and, at each dwell point, the energy transferred to the mask from the decelerated ions excites it and thereby causes it to emit electrons, positive ions, and negative ions. This phenomenon is referred to as *secondary emission*, and the particles emitted are collectively referred to as *secondary particles*.

A device called a *detector*, mounted near the bottom of the ion column, attracts and captures the secondary particles emitted by the mask in response to excitation by the ion beam, and it develops an electrical signal whose magnitude is proportional to the number of particles it is receiving at any given instant. Variations in surface topography and composition that are encountered as the ion beam scans the object being imaged produce variations in the rate of secondary particle emission, which result in variations in the electron current—the signal—produced by the detector. The detector that is normally used is often referred to as the *MCP* (pronounced like the letters), which is the abbreviation for the kind of device that it is: a microchannel plate.

The signal thus detected at successive dwell points is applied to the signal acquisition electronics, where it is filtered for noise-suppression, and digitized to a binary number in the range of 0 to 255 (where 0 is the weakest/darkest signal and 255 is the strongest/brightest signal). As the scan proceeds, the digital values produced by the signal acquisition electronics are stored in successive locations in a random access memory array, called the *frame buffer*, in the graphics board in the FIB system computer.

The frame buffer is read sequentially and continuously in synchronism with the raster scan of the CRT monitor such that the value of each byte of image data determines the combination of red, green, and blue (RGB) signals that lights one dot or pixel on the CRT to a particular gray level. However, the image data may be translated by the software in various ways before it becomes the RGB signal that illuminates pixels on the CRT.

**Imaging Modes** The FIB system uses any of three techniques for capturing secondary emission from the specimen: *electron imaging mode, ion imaging mode*, and a variation of electron imaging mode called *multiplex imaging mode*. In the electron imaging modes, the particle detector is electrically biased to attract and capture electrons; in ion mode it is biased to attract and capture positive ions.

Electron imaging mode often produces clearer images than ion imaging mode because the secondary electron yield from most materials is greater than the secondary ion yield, and the imaging signal

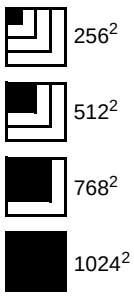
also tends to be less noisy. Also, a lower ion dose can be used for image acquisition. However, if the area being imaged is electrically nonconductive, being either an insulator (e.g. quartz) or a small island of conductive material (e.g. chrome) surrounded by insulating material, it quickly develops a positive electrostatic charge. This is due to the loss of electrons through secondary emission and, to some extent, by the implantation of positive gallium ions. This positive charge can prevent secondary electrons from escaping from the surface of the specimen, thus rendering the mask "invisible" to the imaging process. It can also deflect the ion beam, thus affecting the placement accuracy of repairs.

In ion imaging mode, the detector is biased to attract positive ions, and a *flood gun* (see below), which directs a stream of free electrons at the specimen, can therefore be employed for positive-charge neutralization during rasters. The flood gun cannot be used while the detector is biased to capture electrons because the electron flood would saturate the detector, reducing its useful life and, in any case, totally obscuring electron emission from the specimen.

Multiplex imaging mode is a variation of electron imaging mode in which the detector is switched off, and the flood gun is switched on, during the time that the ion beam is moving *between* dwell points. While the beam is dwelling at any particular point, the flood gun is switched off and the detector is switched on. This has the advantages of both electron and ion modes: clearer images with concurrent charge neutralization. However, it requires significantly more time to produce an image than the other modes and, to be effective, it requires relatively frequent recalibration of the flood gun to verify that it is correctly aimed and energized.

**Imaging Speed** The rate at which an image raster proceeds is generally referred to as the *imaging speed*. The *dwell time*—the time during which the ion beam is directed at each dwell point—is the main determinant of the imaging speed for ion mode or electron mode. For these imaging modes, the retrace time is the same, and the transition time between dwell points is negligible. However, for multiplex imaging mode, the transition time between dwell points and the retrace time are extended to allow charge neutralization and therefore become significant factors. Accura 850 systems provide three imaging speeds—*slow*, *medium*, and *fast*. The overall image size (see below) is also a factor in image acquisition time.

**Image Size** The term *image size* is generally used in reference to the area of the computer screen that is occupied by the image produced by a raster. The application program enables the user to select (through an array of graphics such as those shown here at right) four progressively larger image sizes ranging from 256 by 256 to 1024 by 1024. The numbers refer to the number of pixels on the computer screen (hence *image size*), as well as to the number of dwell points in the image rasters that produce the images (there is a one-to-one correspondence). The numbers are *not* related to the dimensions of the area being scanned to produce the image, which is determined by the field of view selection. However, they do relate to resolution: the larger the image size selected for a given field of view, the greater the dwell point density, and therefore the greater the resolution (and apparent magnification).




**Pixel Averaging** *Pixel averaging* involves sampling the signal from the detector for a series of short periods during the dwell, averaging the signal levels thus obtained, and digitizing that average

as the information for the dwell point. The principle is that, when the signal produced by the particle detector as a result of the impingement of the ion beam at a given dwell point is sampled repeatedly, and is averaged over the number of samples, the randomly-occurring information ("noise") will eventually constitute a relatively small part of the final result, while the valid information will tend to prevail. The duty cycle for the sampling electronics is chosen by the software based upon the dwell time.

**The Flood Gun** The flood gun is an electron-emitting device that is suspended horizontally near the lower end of the ion column to direct a beam of low-energy electrons at the mask in an area roughly corresponding to the field of view. This electron *flood* neutralizes the positive electrostatic charge that tends to build up on the mask during rastering. Electrostatic charge buildup interferes with imaging, and may result in electrostatic discharge that damages the specimen. See "Imaging Modes" on page 45 for related information.

The application program's Power Up function powers up the flood gun as well as the ion column. While it is powered up, the flood gun operates continuously as long as the selected imaging mode is *ion*. It is operated intermittently during imaging rasters while the imaging mode is *multiplex*, and it is blanked (its emission suppressed) while the imaging mode is *electron*. Thus, in general, the operation of the flood gun is automatic and operator intervention is not required. (Although, if the user images a mask in electron mode or multiplex mode, and then proceeds with milling or deposition without switching to ion imaging mode, the flood gun will remain blanked and no charge neutralization will take place. Depending upon the circumstances, this may or may not be desirable.)

The flood gun assembly consists of an electron gun and a cylindrical structure, sometimes called the *snout*, which incorporates an electrostatic lens and a vertical deflection element. The electron gun itself comprises several electrodes (refer to Figure 14):

- Filament: a cathodic electrode consisting of either a small tungsten disk or a short length of tungsten wire. A direct current (the *filament current*) is passed through it to produce thermionic emission of electrons. The power supply that is the source of the filament current is floated on (biased by) a negative potential produced by a power supply, called the cathode supply, such that the filament itself is negative with respect to ground. The electron current that flows from this cathode supply to ground is called the *cathode current*, and it serves as a measure of the output of the gun.

- Anode: Electrons emitted by the filament are accelerated toward and exit through a grounded annular anode at the opposite end of the gun.

- Grid: This is a wire-mesh electrode interposed between the filament and the anode. A negative potential can be switched onto the grid to counteract the acceleration potential between the filament and the anode, and the gun can thereby be blanked (shut off) while preserving a state of filament-readiness.

The electrons pass through the anode and into the snout, where they are directed such that, when they exit the snout and enter the electrostatic field produced by the various potentials on the particle detector, they assume trajectories that takes them to the appropriate area on the specimen.

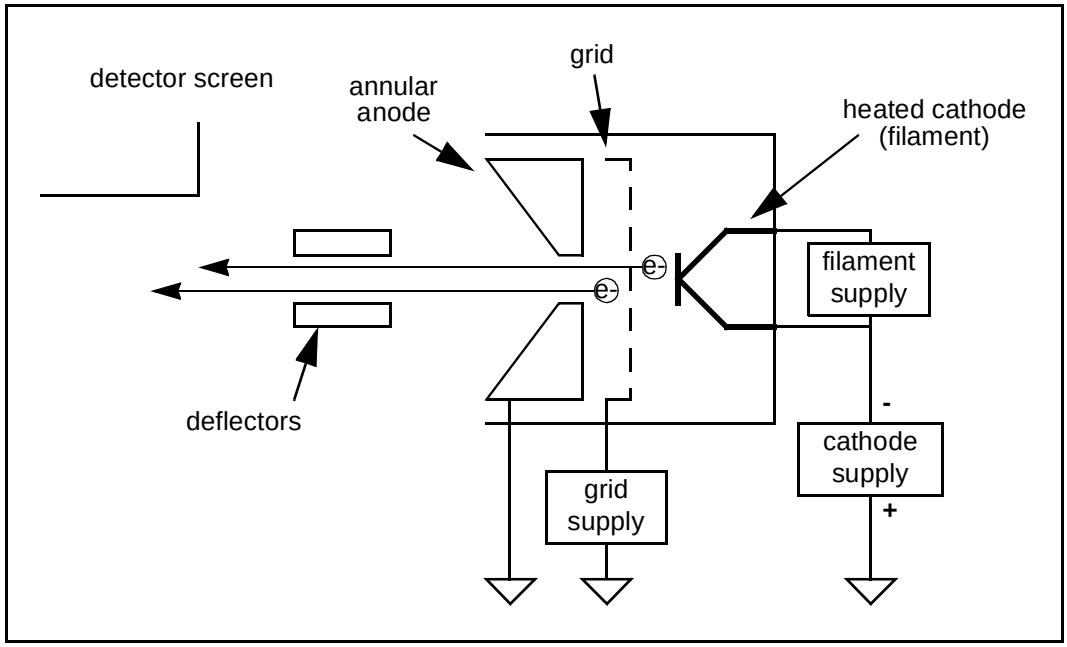



**Figure 14. Schematic Diagram of Flood Gun.**

**The Funnel** The funnel is a shallow pan-shaped metal structure that is suspended below the ion beam column, primarily for the purpose of providing an electrostatic shield between the electron flood and whatever static electric charges may be present on the mask. An orifice in the center of the pan allows the ion beam and the electron flood to pass through to the mask while the funnel itself provides a relatively large grounded plane. A vertical motion mechanism is provided that *extends* (lowers) the funnel to a position close to the mask to maximize its effectiveness during charge neutralization, and that *retracts* (raises) it slightly to provide vertical clearance for maneuvering the stage in the *x-y* plane.

The funnel also serves as a mount for the carbon deposition gas delivery nozzle, as well as for the delivery nozzles for any other chemicals that may be installed in the system.

**The Stage** The ion column is stationary, and its field of view (scan field) is relatively small. Therefore, a moveable stage is incorporated to allow the mask to travel about in the *x-y* plane to bring points of interest under the column. The stage is implemented with piezoelectric linear drive mechanisms as depicted by Figure 15. Working travel is ±4 inches (±100 mm) from center, which accommodates masks up to 7 inches (200 mm) square, and allows diagnostic fixtures (see below) on the stage to be positioned under the column.

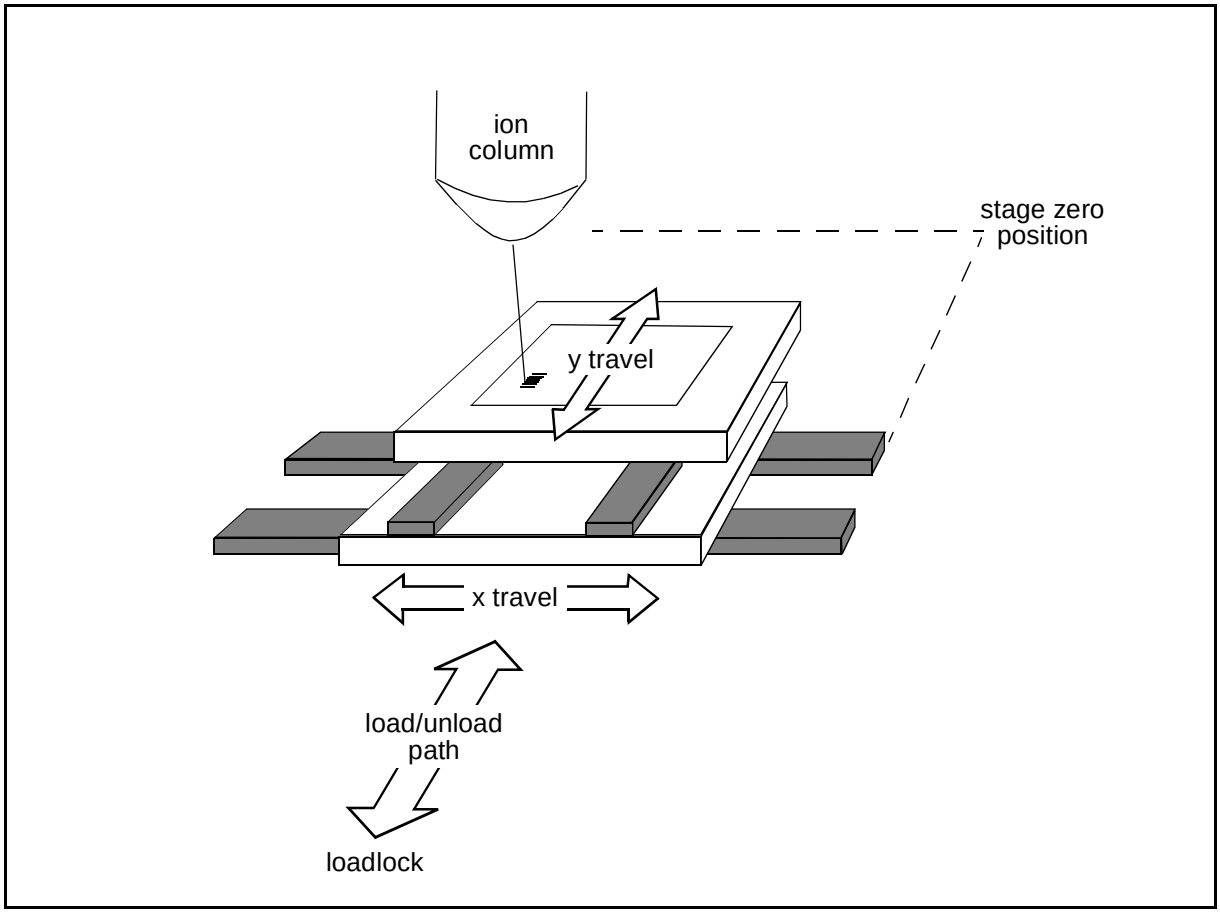



**Figure 15. X-Y Stage Motion.**

**Positioning Server** [A software program known as the *positioning server* operates the stage at the hardware server level. It maintains an awareness of the position of the stage, and processes requests for stage motion by application programs.

**Stage Motion Controls** The FIB system user can move the stage with a *joystick*, or with a variety of controls provided by the application software. The joystick operates the stage directly through the computer's USB port (using DirectX drivers); other controls operate by requesting actions through the stage positioning server. Stage motion for the purpose of positioning defect sites on the mask under the ion column is normally controlled by the application software (through the positioning server) based upon inspection data provided for the mask.

**Stage Zero** The stage's position (or *address*) is registered by hardware counters as its displacement in *x* and in *y* from mechanical switches that define the right-rear limit of its travel (see Figure 15). Thus, the stage's position address increases as it moves away from this reference position and decreases as it moves toward it. The reference position is referred to as *Stage Zero*. The stage

can be sent to this position (*zeroed*) whenever the indication of its current position becomes suspect (for example, when system power is restored after having been interrupted).

**Stage Labels** The addresses of various stage positions are recorded in files called *stage labels* so that the positioning server software can send the stage to any of them when requested to do so by the application program. Included are stage labels for the *load position* (in which the stage is docked such that a mask can be moved between it and the loadlock) as well as stage labels for placing the geometric centers of masks of various sizes are under the ion column, and stage labels for placing diagnostic fixtures (see page 52) on the stage under the column.

**Registration** The positioning of successive masks on the stage must be repeatable in the *x-y* plane so that, given the Cartesian coordinates of defect sites found on a mask by an inspection system, a predetermined transformation can be applied to obtain the FIB system stage coordinates that will bring the defect sites under the ion column. It must also be vertically repeatable because FIB process parameters for mask repair presuppose a fixed relationship between the top surface of the mask, the electron funnel, and the ion column. The repeatable positioning of masks in these respects involves the use of *registration* surfaces against which a mask is brought to bear. The internal (or chamber) robot places the mask on the *mask holder*. The mask holder uses small drive motors and registration pins to register the mask on the stage in the x, y, and z planes.

**The Mask Holder** The mask holder mechanically accepts a 6-inch square mask (or "reticle") that is transferred from the internal robot. The internal robot places the mask onto the mask holder to an accuracy within several thousandths of an inch, then retracts to its home position. The mask rests on three spherical registration buttons whose z-axis height and coplanarity are aligned with a high degree of accuracy. This ensures the surface of the mask is properly located in the reference plane. The buttons are manufactured from a high performance thermoplastic called polyetheretherketone (PEEK), and support the mask approximately 2mm in from the side and rear edges. Small drive motors are then employed to bank the mask squarely against three rotating banking pins (that are also manufactured from PEEK). The banking mechanism (which is mounted underneath the mask holder) applies a light force to the lower right corner of the mask, pushing it left against two alignment pins and forward against the remaining pin. The banking mechanism consists of a 12mm diameter cam driven by an 8mm diameter DC motor. The cam directs a pivoting v-block riding on a low profile ball slide, which applies a spring force to the mask and holds it firmly in place. When the mask is in position, it is recognized by a presence sensor as being properly in place, and the stage is then free to move. Figure 16 shows the mask holder, and Figure 17 shows a mask positioned on the mask holder.

**The Mask Carrier (RSP)** A *mask carrier* -- also referred to as an RSP (Reticle SMIF Pod) is a square, pan-like carrier that holds a mask plate of a particular size. The mask carrier protects the mask plate (or reticle) against abrasion and particulate contamination while it is being transported to and from the FIB system.

**Loading & Unloading** To load a mask, the user places an RSP (Reticle SMIF Pod) at the top of the Load Port Module (also referred to as the SMIF pod). The user then opens the Load/Unload dialog box by clicking Load/Unload on the [Menu Name] menu. Next, the user selects a plate size [???](5, 6, or 7 inches) and a plate file, then clicks the Load button at the bottom of the dialog box.

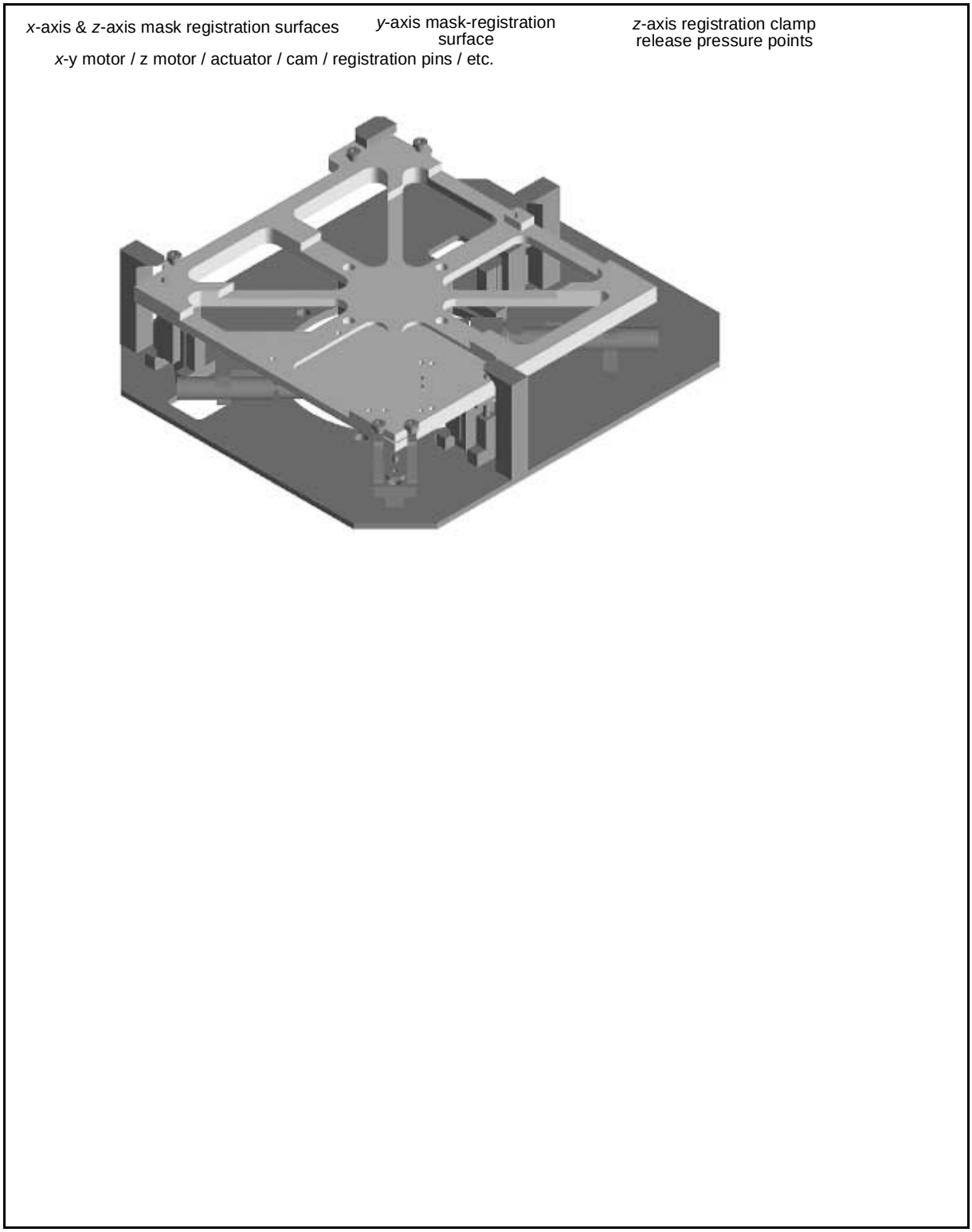

*x*-axis & *z*-axis mask registration surfaces
*y*-axis mask-registration surface
*z*-axis registration clamp release pressure points
*x*-y motor / z motor / actuator / cam / registration pins / etc.

**Figure 16. The Mask Holder**

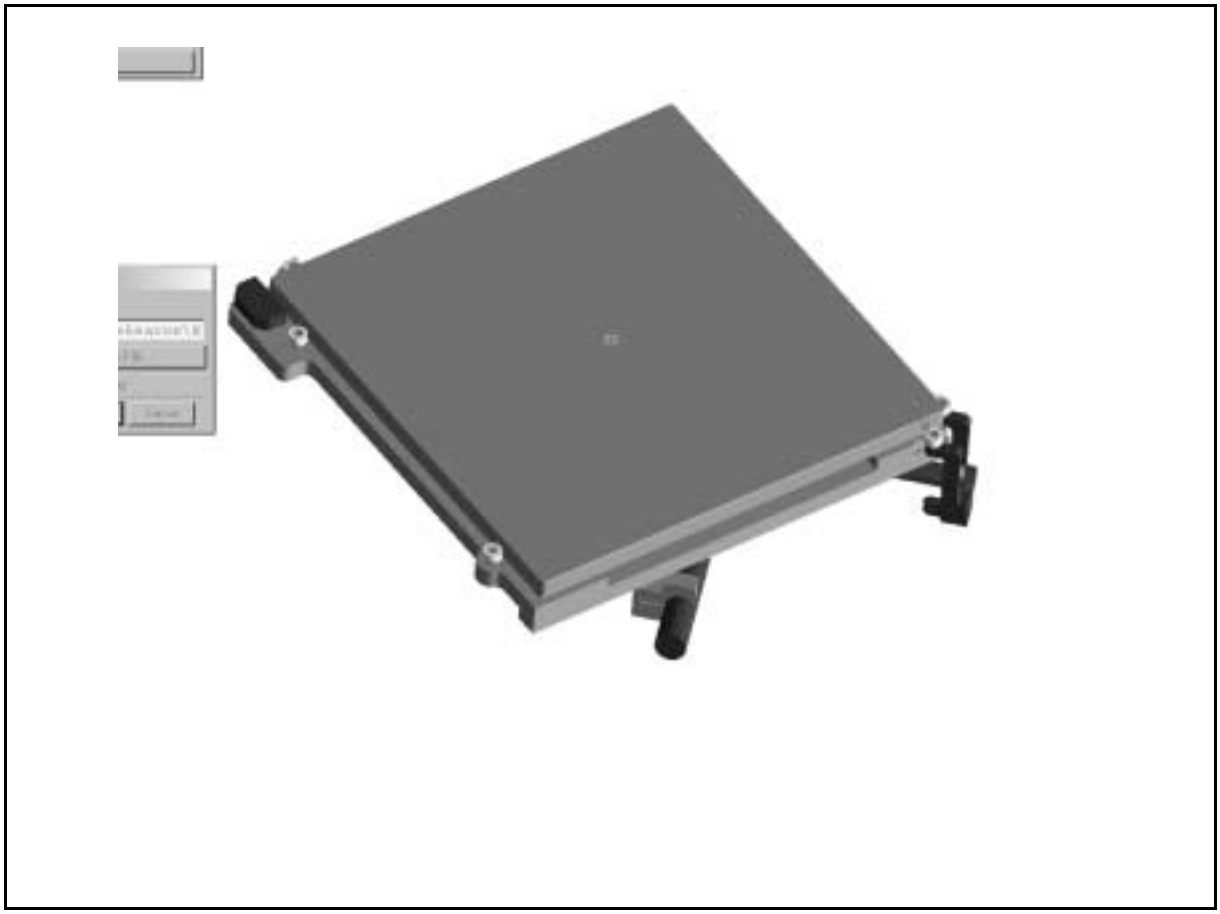


**Figure 17. Mask Holder with Mask in Place**

[See Figure 18 -- Mask Carrier (RSP)] An automated loading system -- involving two transfer robots and automated alignment mechanisms -- transfers the mask to the positioning stage. When imaging and repair procedures are complete, the mask is automatically returned to its mask carrier in the load port module.

**Diagnostic Fixtures** Refer to Figure 19. Several devices that are used for alignment and calibration are mounted near the rear edge of the stage. These include the *silicon grid*, the *ion faraday*, and the *electron faraday*. The stage position that places each of these devices under the ion column is recorded on disk as a stage label file so that the software can bring them into play whenever necessary. A solid state sensor for gauging workchamber temperature is also mounted on the worktable. The other devices are explained below.

**The Silicon Grid** The silicon grid is a flat silicon chip, about 10 mm by 16 mm, on which is etched a grid of 5-micron lines on 35-micron centers. It is used as an imaging target for various system alignments. When the mask plate is registered on the stage, its top surface is in the same horizontal plane as the top surface of the silicon grid.

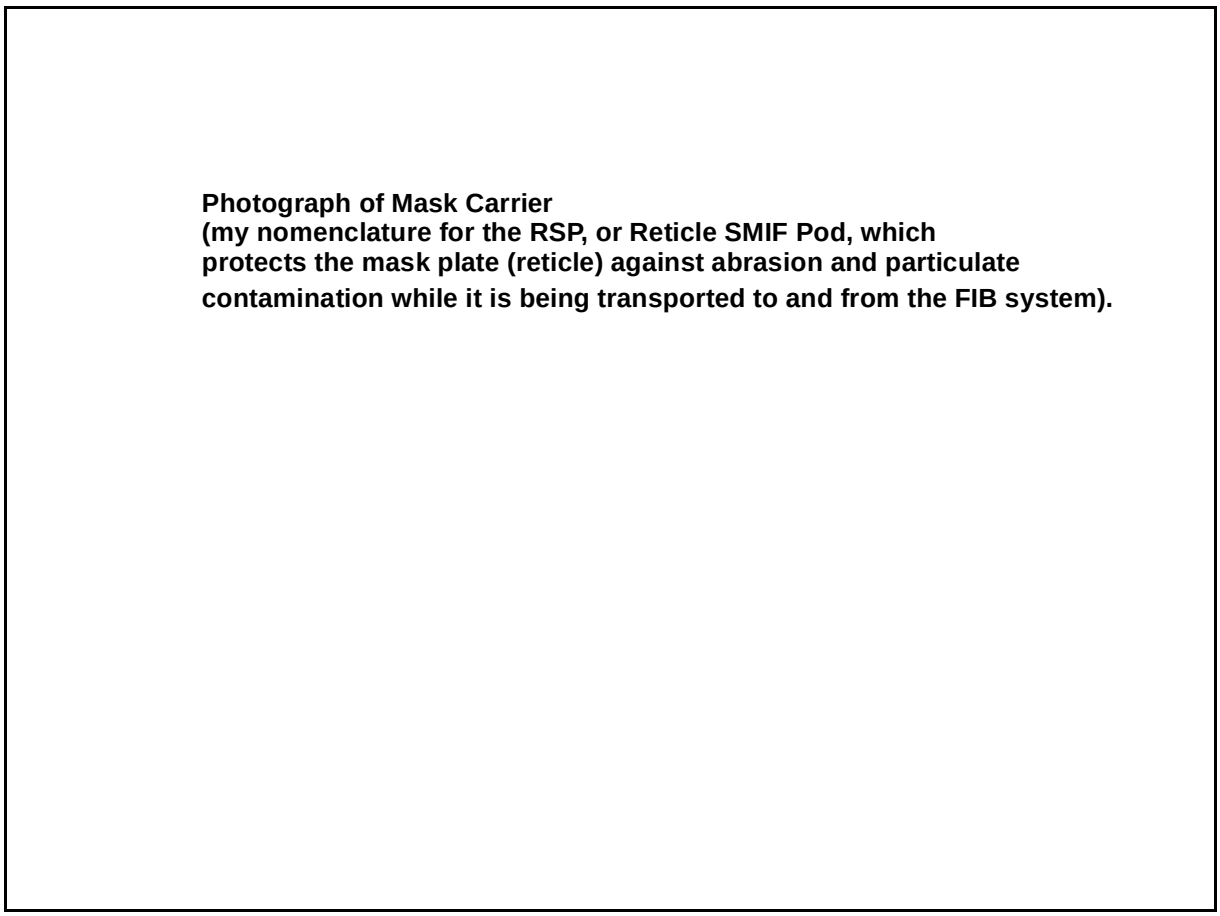

Photograph of Mask Carrier
(my nomenclature for the RSP, or Reticle SMIF Pod, which
protects the mask plate (reticle) against abrasion and particulate
contamination while it is being transported to and from the FIB system).

**Figure 18. The Mask Carrier**

**The Ion Faraday** The ion faraday is a small cup-like structure used to measure the ion beam current being delivered by the column. It provides an alternative to using the beam blanking aperture element (page 41) to measure the beam current. Also, the ion faraday has across its opening a metal grid structure that serves as a convenient imaging target for performing various alignment tasks such as stigmation. The grid is about 3 mm in diameter, the bars in the grid are roughly 30 to 50 microns wide, and the spaces between the bars are about 110 to 135 microns wide.

To measure the beam current with the ion faraday, the stage is positioned so the beam can be directed through an opening in the grid and onto the floor of the cup. The cup is connected to electrical ground through an electron current metering circuit in essentially the same manner as is the blanking aperture.

The ion faraday cup may provide a slightly more accurate measure of beam current than the beam blanking aperture element because the walls of the cup usually capture all of the secondary particles that are emitted in the cup as a result of ion bombardment. Although a set of elements is installed

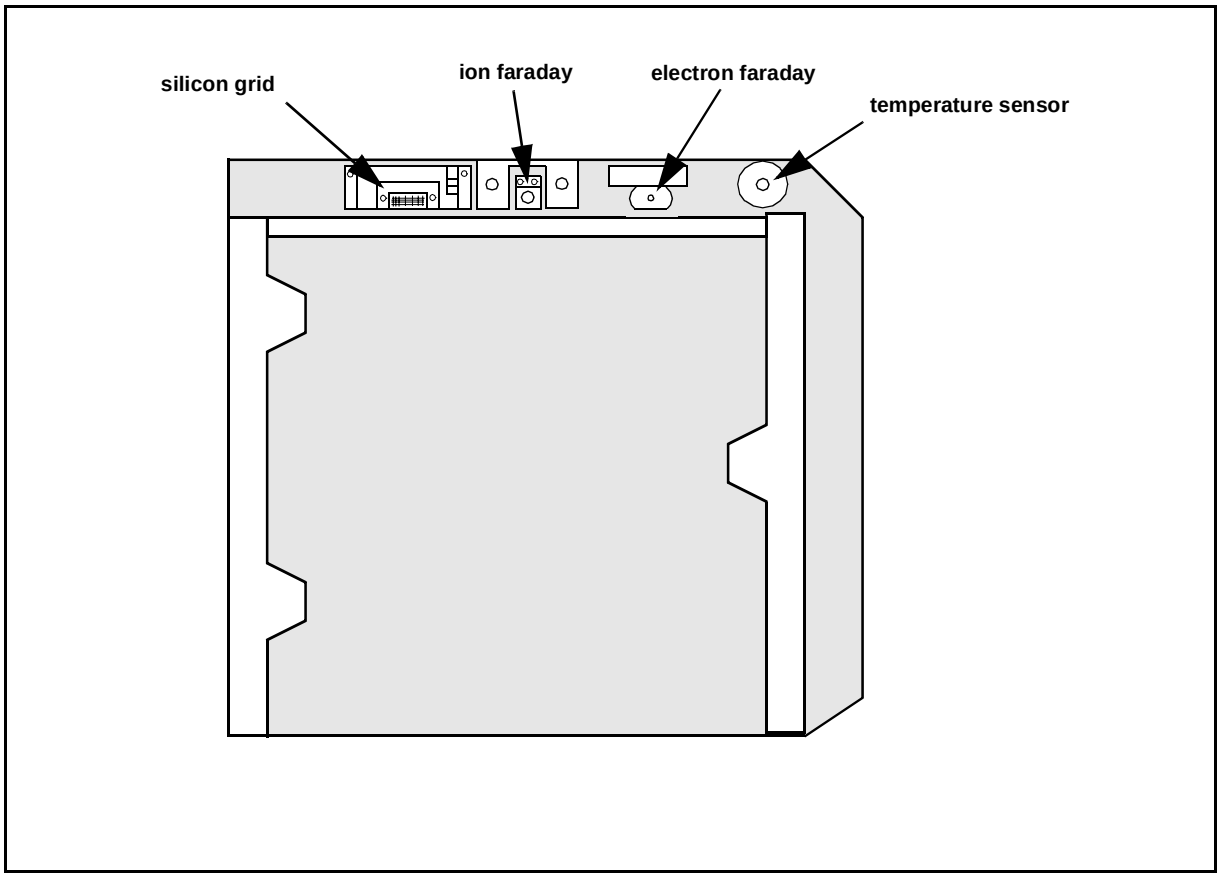



**Figure 19. Diagnostic Fixtures on the Stage.**

in the column in proximity to the beam blanking aperture element to suppress secondary electron emission while trapping positive secondaries, some electrons or other negative particles may still escape to other parts of the column, thus drawing extra electron current through the metering circuit and yielding beam current readings that are slightly high.[3] However, in general, the blanking aperture is a preferable metering point for beam current because obtaining a reading does not require the stage to be repositioned.

**The Electron Faraday** The electron faraday measures the electron output from the flood gun. It is physically and operationally similar to the ion faraday (see above), but it measures electron current from the cup to electrical ground instead of vice versa, and it does not have the grid structure across its opening.

**Stage Position Tracking** The piezoelectric drive motors for the FIB system's stage can position the stage to within 100 nanometers of an *x-y* address called for by the software. Thus, when the software calls for a particular point on the mask to be brought directly under the center line of the

[3] For the same reason, it is essential that, when a faraday reading is taken, the stage be positioned so that the beam passes through an opening in the grid. If it strikes any part of the grid, a significant amount of secondary electron emission from the affected area will escape upward, thereby causing an erroneously high reading.

ion beam column, that point may in fact be as far as 100 nanometers from the center line on either or both axes when the stage comes to rest. The software can compensate for this *position error* by, in effect, moving the ion beam column's scan field off-center, but it must know what the error is. This information is provided by laser interferometers or linear encoders for each axis.

**Interferometry** Refer to Figure 20, which illustrates how interferometry works on one axis. Simply

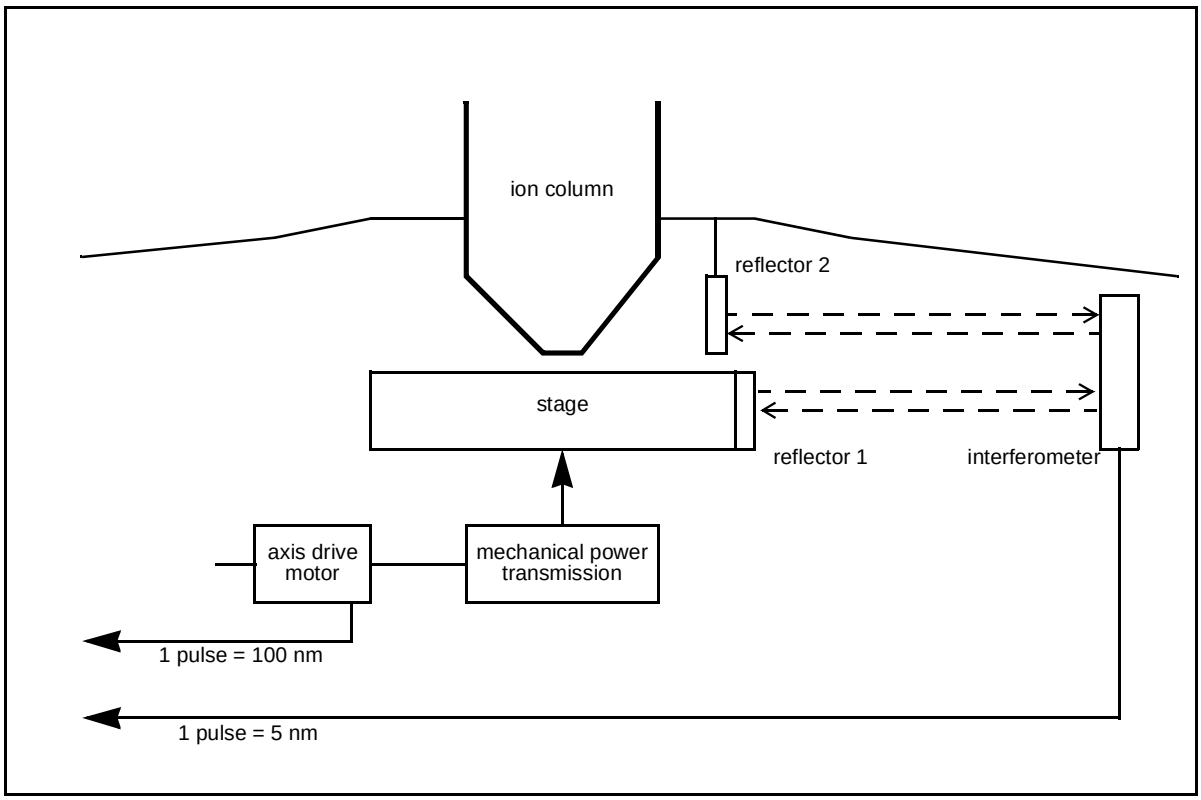



**Figure 20. Stage Position Tracking.**

put, the interferometer directs a laser beam along the axis to a mirror mounted on the side of the stage (*reflector 1*), and compares the wave length of the reflected light with that of the transmitted light. While the stage is moving along the axis toward the interferometer, the phenomenon known as the *Doppler effect* causes the wave length of the reflected light to appear shorter than the wave length of the transmitted light. Conversely, while the stage is moving away from the interferometer, the apparent wave length of the reflected light appears longer than that of the transmitted light. Interference patterns resulting when the two light beams are combined provide detectable pulses that can be directly correlated with distance moved.

The digital counters that register stage position are reset to zero when the stage is at the Stage Zero reference position, and then are incremented by pulses produced by the interferometers as the stage moves away from the reference position, and decremented as it moves back.

A reference mirror mounted in a fixed position in proximity to the ion beam column allows the interferometer to detect and compensate for relative motion between itself and the stage that results from thermal expansion or contraction of the workchamber. The net effect is that the interferometers indicate motion in increments of 5 nanometers.

The arrangement illustrated in Figure 20 is duplicated, at 90°, for the other axis. The mirror for each axis is wide enough, and carefully aligned, so that motion on one axis is undetectable by the interferometer for the other axis.

**Linear Encoders** If an interferometer indicates an error condition (for example, an interruption of the laser beam by a foreign object), stage motion feedback to operate the position counters is available from *linear encoders* that are incorporated in the stage piezoelectric drive motors. As a drive motor moves, its encoder produces digital pulses that indicate displacement, from which stage motion can be extrapolated.

## Vacuum

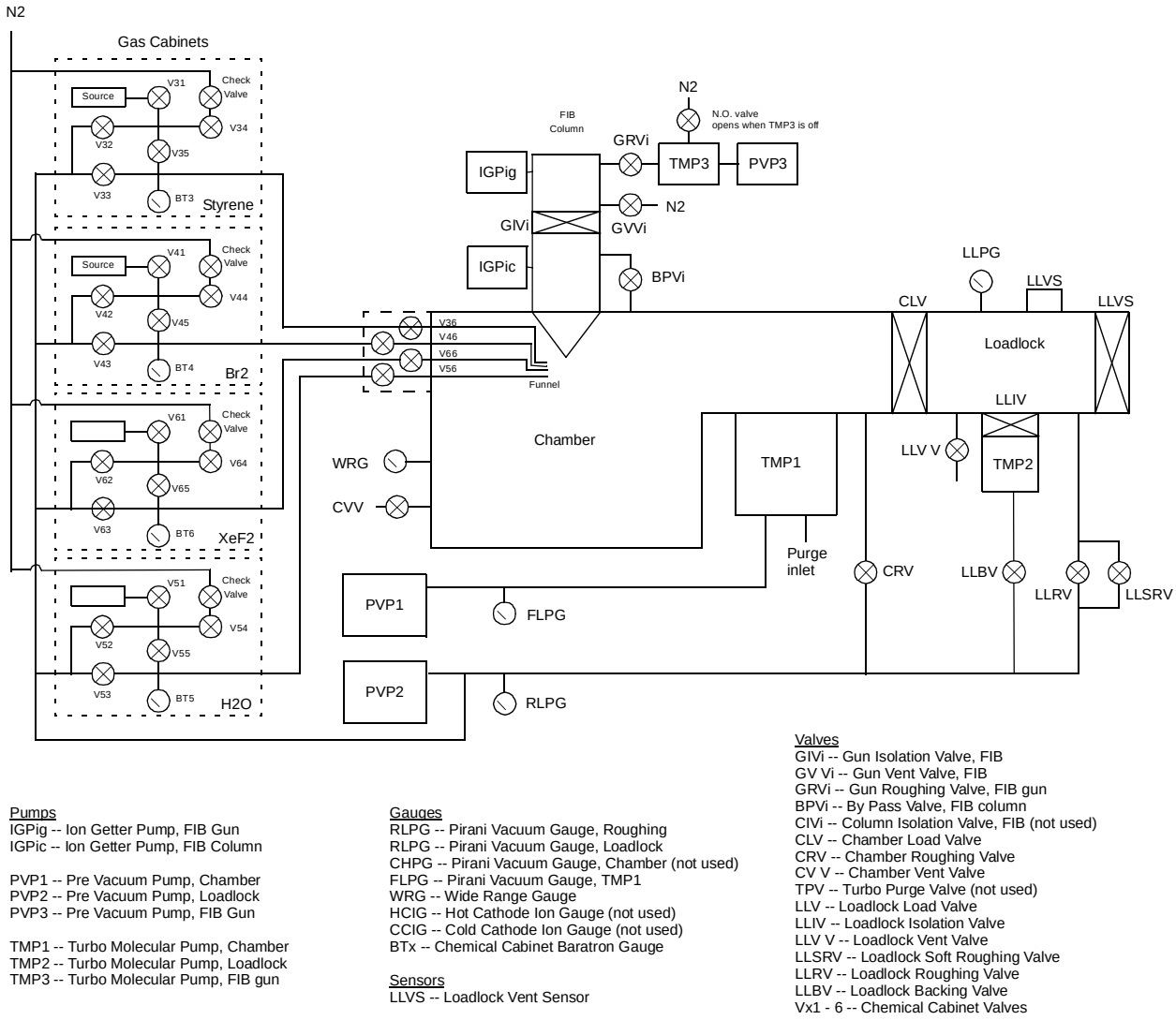
The ion beam can be generated only in an extremely low-pressure environment, which is to say, an enclosed space as nearly devoid of gas molecules as is feasible. This is because the intense electrostatic fields in the column will ionize any gas molecules that might be present. Ionized particles conduct electricity if the particle density is such that electrons can jump from particle to particle. Thus, if the column is powered-up with enough gas present, electrical arcs will occur between electrodes, electrode vaporization and ion implantation will occur, and the column will thereby be damaged or destroyed. Ionized particles are also accelerated to electrodes having an opposing charge, where they accumulate, eventually affecting the operation of the column. For these reasons, as well as for the safety of service personnel, the FIB system is interlocked such that an abnormal rise in internal pressure switches off the high voltage to the column.

The need to keep the interior of the ion column evacuated when power is applied to it dictates that the workchamber must also be evacuated. This is because the opening through which the beam passes at the bottom of the column will admit gas molecules and, in any case, the beam would dissipate after exiting the column if it encountered atmosphere. Also, the imaging scheme involves the use of a particle detector that is mounted on the outside of the bottom of the column. If the operating voltages are applied to this detector while it is exposed to atmosphere, it can be damaged or destroyed.

Maintaining an adequately low gas pressure requires continuous pumping because gas molecules drift into the evacuated spaces from various sources within the system itself. These sources include lubricants, electrical cable insulation, and atmospheric gases and water vapor that are adsorbed by the interior surfaces of the workchamber when the workchamber is opened for servicing. Also, whenever a mask plate is brought into the workchamber, some adsorbed atmospheric gases and water vapor inevitably enter with it. Finally, the pressure in the workchamber normally rises when a process gas is introduced for deposition or gas-assisted etching.

### Vacuum System Schematic

A schematic diagram for the vacuum system is shown in Figure 21.




Pumps
IGPig -- Ion Getter Pump, FIB Gun
IGPic -- Ion Getter Pump, FIB Column

PVP1 -- Pre Vacuum Pump, Chamber
PVP2 -- Pre Vacuum Pump, Loadlock
PVP3 -- Pre Vacuum Pump, FIB Gun

TMP1 -- Turbo Molecular Pump, Chamber
TMP2 -- Turbo Molecular Pump, Loadlock
TMP3 -- Turbo Molecular Pump, FIB gun

Gauges
RLPG -- Pirani Vacuum Gauge, Roughing
RLPG -- Pirani Vacuum Gauge, Loadlock
CHPG -- Pirani Vacuum Gauge, Chamber (not used)
FLPG -- Pirani Vacuum Gauge, TMP1
WRG -- Wide Range Gauge
HCIG -- Hot Cathode Ion Gauge (not used)
CCIG -- Cold Cathode Ion Gauge (not used)
BTx -- Chemical Cabinet Baratron Gauge

Sensors
LLVS -- Loadlock Vent Sensor

Valves
GIVi -- Gun Isolation Valve, FIB
GV Vi -- Gun Vent Valve, FIB
GRVi -- Gun Roughing Valve, FIB gun
BPVi -- By Pass Valve, FIB column
CIVi -- Column Isolation Valve, FIB (not used)
CLV -- Chamber Load Valve
CRV -- Chamber Roughing Valve
CV V -- Chamber Vent Valve
TPV -- Turbo Purge Valve (not used)
LLV -- Loadlock Load Valve
LLIV -- Loadlock Isolation Valve
LLV V -- Loadlock Vent Valve
LLSRV -- Loadlock Soft Roughing Valve
LLRV -- Loadlock Roughing Valve
LLBV -- Loadlock Backing Valve
Vx1 - 6 -- Chemical Cabinet Valves

**Figure 21. Vacuum System Schematic.**

**The Loadlock** The *loadlock* is an air lock that allows the mask to enter and leave the workchamber without requiring the workchamber to be completely vented and re-pumped. The loadlock opens to atmosphere through an outer door called the *loadlock door*, and it opens to the workchamber through a wide vertically-operating gate valve called the *chamber door* (*CLV* in Figure 21).

**Venting** To minimize adsorption of atmospheric gases when any part of the vacuum system must be vented to atmospheric pressure, nitrogen gas ($N_2$) is admitted to equalize the internal and external

pressures. This occurs, for example, whenever the loadlock is vented to atmospheric pressure at the end of the unloading sequence.

**Vacuum Server/Controller** A software program known as the *vacuum server* runs in the system computer concurrently with the application program (and other servers). It maintains an awareness of the status of the vacuum system, and it processes requests for vacuum actions by the application program. This involves translating high-level requests (for example: “load a mask plate”) to the actual sequence of low-level commands involved in carrying out the request (for example: “open valve V1,” “open valve V4,” etc.). The vacuum server sends the low-level commands through a communications link to a continuously-running firmware program that is stored in read-only memory in a hardware device called the *vacuum controller*. The program in the vacuum controller includes *firmware interlocks* whereby it is coded to reject commands that, in context, would be unsafe or damaging. Thus, for example, if a malfunction resulted in the vacuum server issuing a command to close valve CLV (the loadlock/workchamber door) while the transport mechanism was still in the process of loading a mask plate onto the stage, the vacuum controller program would reject the command. The vacuum controller’s firmware program is also capable of *automatic actions* under certain conditions. For example, the program will open the high voltage interlock circuit to power-down the ion column if the pressure in the workchamber rises to a level above which arcing can be expected.

**Ion Gun Isolation Valve** Designated *GIVi*, this valve can be closed by the vacuum server to maintain vacuum in the lower part of the ion column when the upper part of the column must be vented to atmospheric pressure to allow service access to the ion source and/or the beam-limiting apertures. The service apparatus that vents and pumps the upper column area is enabled only when GIVi is closed. The service apparatus includes a controller that allows one-button venting, and one-button pumping, of the upper column area. See Figure 10 on page 38 for the location of GIVi in the ion column.

## Gas Pressure

**Units** The relative vacuum in the FIB system is expressed in terms of *gas pressure.* The international (SI) unit of measurement for pressure is the *pascal* (Pa). The customary unit of measurement for gas pressure in the United States in the context of vacuum technology is the *torr*. One pascal is equivalent to $7.5 \times 10^{-3}$ torr (1 torr is equivalent to $1.3 \times 10^{2}$ pascal). Gas pressure in the workchamber is typically maintained in the range of $10^{-5}$ Pa ($10^{-7}$) torr, which is roughly one billionth of atmospheric pressure.

**Pressure Gauges** Mechanical pressure gauges do not work at the low pressures normally sought in the FIB system. The number of gas molecules that would find their way into such a gauge would be so small that the mechanism would not respond. Therefore, operating pressure in the workchamber is measured by a combination of *thermocouple* gauges and either a *hot-cathode ionization gauge* (HCIG) or a *cold-cathode ionization gauge* (CCIG). These work as follows.

**Thermocouple (TC) Gauges** are used at several locations in the FIB system to indicate gas pressure from atmospheric pressure down to the rough-vacuum range, which is about 1.3 Pa ($10^{-2}$ torr). They

apply two principles: that a junction of dissimilar metals develops a voltage proportional to the temperature of the junction, and that, when the junction is heated and placed in a gaseous environment, the heat escapes from the junction by convection at a rate proportional to the ambient gas pressure. Thus, the lower the gas pressure, the hotter the junction remains, and the higher the voltage it develops. The voltage is measured by an electrical metering circuit and a predetermined correlation between voltage and gas pressure is used to derive the reading. At pressures below 1.3 Pa ($10^{-2}$) torr, the gauge "bottoms out" (produces its lowest reading) because the convection of heat from the device becomes negligible.

**Ionization Gauges** are used to obtain pressure readings in the workchamber when the pressure therein is below the range of the TC gauge. Two types of ionization gauges have been installed in FEI 8000 Series systems: *hot cathode ionization gauges* (HCIGs), or *cold cathode ionization gauges* (CCIGs).

The HCIG consists of a glass envelope attached to a port at the rear of the workchamber in which several electrodes are mounted, and associated electronics located in the FIB system's electronics module. The gauge works by heating a cathode element to produce thermionic emission of electrons. The electrons are accelerated to a wire grid having a positive potential and, as they pass through the gas present in the glass envelope to reach it, they ionize the gas molecules by colliding with them and displacing their outer-orbit electrons. The displaced electrons ionize more gas molecules, etc. The ionized gas molecules, being deficient in electrons and therefore positively charged, are attracted to a negative electrode. Their arrival at that electrode draws electron current from the power supply providing the negative potential, and this electron current provides the measure of gas pressure in the envelope.

The CCIG works on the same ion-collection principle that the HCIG employs except that, instead of using electron bombardment to ionize the gas molecules, it uses a strong magnetic field. It is thus similar to an ion pump (see "Ion Pumps" on page 60).

## Vacuum Pumps

**Turbopump** A turbomolecular pump—usually referred to as the *turbopump*—pumps through a large opening in the bottom of the workchamber to obtain and maintain high vacuum in the chamber. A turbopump is essentially a high-speed fan, with turbine-like blades that rotate at about 40,000 rpm. However, it cannot achieve or sustain this rotational speed unless the gas pressure to which it is exposed is already relatively low. Therefore, it must be used in combination with an auxiliary vacuum pump, called the foreline pump,[4] that is connected to its exhaust outlet (through a vacuum hose called the *foreline*). See "Auxiliary Pumps" below. The standard turbopump on the Accura 850 system is a water-cooled Varian model *1000HT*.

**Auxiliary Pumps** The system is equipped with two auxiliary vacuum pumps—a *roughing pump* and a *foreline pump*—that are capable of achieving "rough vacuum" (pressures of 1.3 Pa or $10^{-2}$ torr or lower). These pumps, both of which run continuously, are used as follows:

[4] The foreline pump may also be referred to as the *forepump* or the *backing pump*.

- During system pumpdown (when vacuum is being restored after the workchamber has been vented to atmospheric pressure), both pumps work in parallel to evacuate the entire system to rough vacuum so that the turbopump can then be switched on.

- While the turbopump is running, the forepump runs maintains adequately low pressure in the turbopump's foreline.

- When a mask has been placed in the vented loadlock and the loading sequence is to begin, the roughing pump evacuates the loadlock so that the chamber door (V6) can be opened without resulting in a major pressure surge in the workchamber. See page 57 for more information about the loadlock.

The standard foreline pump for the XT100 system is the Alcatel model ACP 20G. The standard roughing pump is the Alcatel Drytel model 34C. Both are "dry" pumps, meaning that they do not use liquid lubrication ("pump oil") for their moving parts.

The auxiliary pumps produce mechanical vibrations and therefore must reside outside the process module enclosure to minimize the transmission of those vibrations to the workchamber. They may be installed behind the FIB system (as shown in Figure 22), or on subflooring below it.

A *foreline isolator* is interposed between the forepump and the foreline. This consists of ballast (mass—for suppressing the transmission of forepump vibration to the foreline), an isolation valve (which the application software can close to protect the turbopump against a sudden gas load if the gas pressure in the foreline should start rising for any reason), and a pressure sensor (which allows the application software to monitor the pressure in the foreline).

The effective pumping capacity ("pumping speed") of the auxiliary pumps is limited by the conductance of the vacuum hoses, which increases with internal hose diameter and decreases with length. Therefore, to obtain adequate pumping speed, the vacuum hoses are made as short as is feasible.

**Ion Pumps** To help maintain high vacuum in the ion column without introducing mechanical vibrations, an ion pump is attached to the lower column housing, and a second ion pump is attached to the upper column housing to maintain very high vacuum in the ion source housing. Each has a separate roughing duct and roughing valve, but the same controlling signal operates both valves simultaneously; they are collectively known as *VI*. {new column pumping information tk}

An ion pump works by ionizing gas molecules with an intense electrical field. By virtue of their charge, the ions are accelerated to, and become implanted in, a cathode structure having a very large surface area.[5] The electrons freed by the ionization process are accelerated in the opposite direction to the anode. Thus, an apparent DC flow through the pump occurs as the free electrons arrive at the anode, and the ions arriving at the cathode are neutralized by cathode electrons. This current is

[5] The surface area is large enough so that, at operating pressures of $1.3 \times 10^{-4}$ Pa ($10^{-6}$ torr) or less, the life expectancy of an ion pump may be well in excess of 50,000 hours.

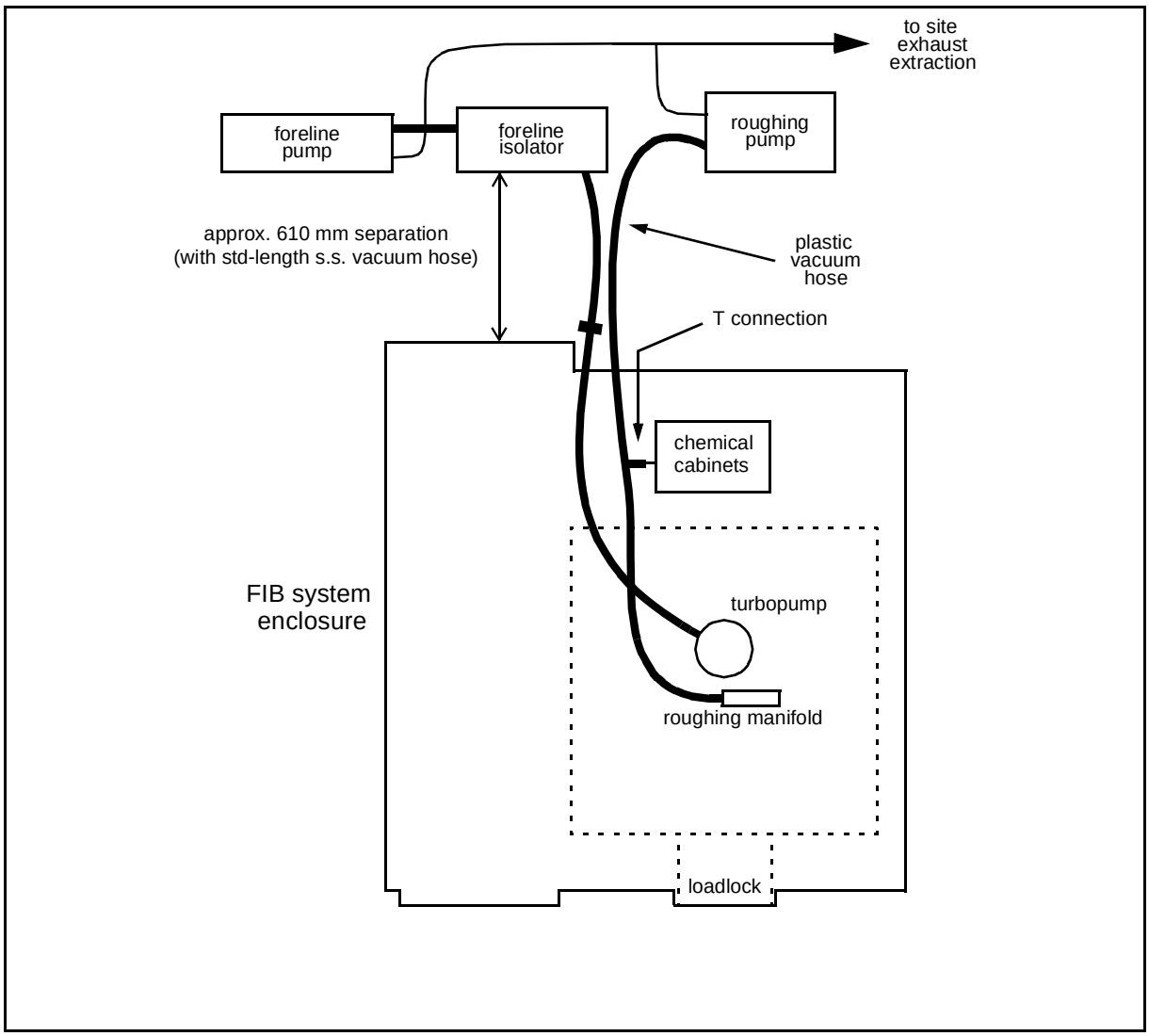



**Figure 22. Auxiliary Vacuum Pump Configuration (Top View).**

proportional to the number of gas molecules being ionized, is therefore proportional to the gas pressure in the pump.

**FIB Chemistry** Any of several *process chemicals* may be used in conjunction with the ion beam in the course of repairing a mask. The source for each of the chemicals is stored in one of four chemical cabinets mounted in a vertical stack inside the rear of the process module enclosure. Process chemicals are delivered, under control of the application software, by a system of delivery lines and control valves, to nozzles mounted on the Funnel (see page 48), from which they are directed at the mask in the vicinity of the ion beam scan field.

**Clear Repairs** Clear defects (missing absorber material) are repaired by *carbon deposition*—the layering of a carbonaceous film onto the mask. The source of the film is a hydrocarbon solvent commonly known as *styrene* or *vinyl benzene.* A small amount of this chemical is stored in a cooled and insulated cylinder in a dedicated chemical cabinet. The cylinder is cooled by a solid state heat transfer device with an air-cooled heat sink to about 10 °C below ambient to minimize condensation of the vapor elsewhere in the delivery apparatus. The delivery valve is opened and the vapor is flowed onto mask in the vicinity of the defect while it is being rastered by the ion beam. Much of it dissipates into the workchamber and is removed by the vacuum pumps, but a monolayer is adsorbed by the surface of the mask. As the ions pass through this monolayer, they decelerate rapidly, which results in an energy transfer that dissociates the gas molecules and fixes the carbonaceous material to the surface of the mask. Many repetitions of the raster are conducted to build up successive layers of the material until the desired thickness is obtained. Thus, the rastering technique for carbon deposition involves many iterations of a raster that precisely administers a relatively low ion dose (if the dose is too low, the material will not adhere; if it is too high, the ion milling effect will dominate.) Serpentine scanning is typically used to minimize the blanking tail effect (see "Rastering" on page 43 for related information).

**Opaque Repairs** Opaque defects (unwanted absorber material) are repaired by milling (sputter-etching) the material away with the ion beam. The relatively massive and highly accelerated gallium ions bombard the material, breaking molecular and atomic bonds and scattering the loosened particles more or less randomly in all directions. Most of the debris is propelled away from the worksite and is removed from the workchamber by the vacuum pumping apparatus, although, without the use of process chemicals, a certain amount can be expected to be *redeposited* on the mask in the area being scanned.

**Chrome-GAE** The chrome-GAE (gas-assisted etching) repair process involves the introduction of a process gas, consisting of a mixture bromine and water vapor, to the defect area while it is scanned by the beam. This gas reacts with the sputtered chrome to form molecules that are *volatile* in that they tend not to stick to whatever surface they might strike, but move about in the workchamber until they are removed by the vacuum pumps. This reduces the amount of material that is redeposited on the mask. The presence of the gas also reduces the sputtering effect of the ion beam on the quartz glass substrate. The net effect is an enhanced selectivity of chrome removal and a reduction in the ion dose required for a given repair. This dose-reduction is significant because the relatively high ion dose otherwise required for chrome removal tends to result in "riverbeds" (see below) and gallium ion implantation, both of which reduce the transmission of short wave length light through the quartz and thereby compromise the quality of repairs. The reservoir for the bromine used with the chrome-GAE process is refrigerated to –12 °C (10.4 °F) by a thermostatic control system that includes a current-regulated power supply mounted in the Electronics Module and a water-cooled heat sink with a remotely-located recirculating refrigeration unit. The water vapor used with the chrome-GAE process is stored in its chemical cabinet at room temperature.

**Riverbeds** A "riverbed," so-called because, in a SEM image it seems to resemble a dry riverbed, is the outline of an opaque defect that has become etched into the glass substrate in the course of removing the chrome; see Figure 23.

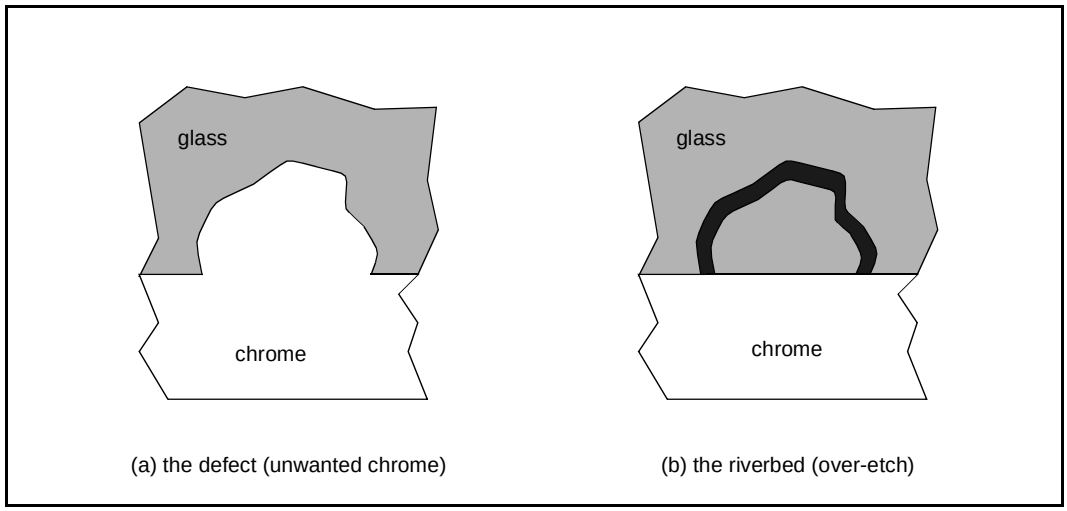



**Figure 23. A "Riverbed."**

"Riverbedding" (also called "the riverbed effect") tends to occur because the sputtering rate is usually greater at the perimeter of a chrome defect than it is in the interior, a phenomenon that seems to be a consequence of the edges or sides of chrome features (defects included) typically sloping outward from top to bottom; see Figure 24. Whether the low relative angle of incidence of the ions increases the sputtering effect (as suggested by the illustration), or the average thickness is less, the practical implication is that the ion dose that will remove the interior of a chrome defect without damaging the glass substrate will tend to over-etch, and produce a riverbed, at the perimeter.

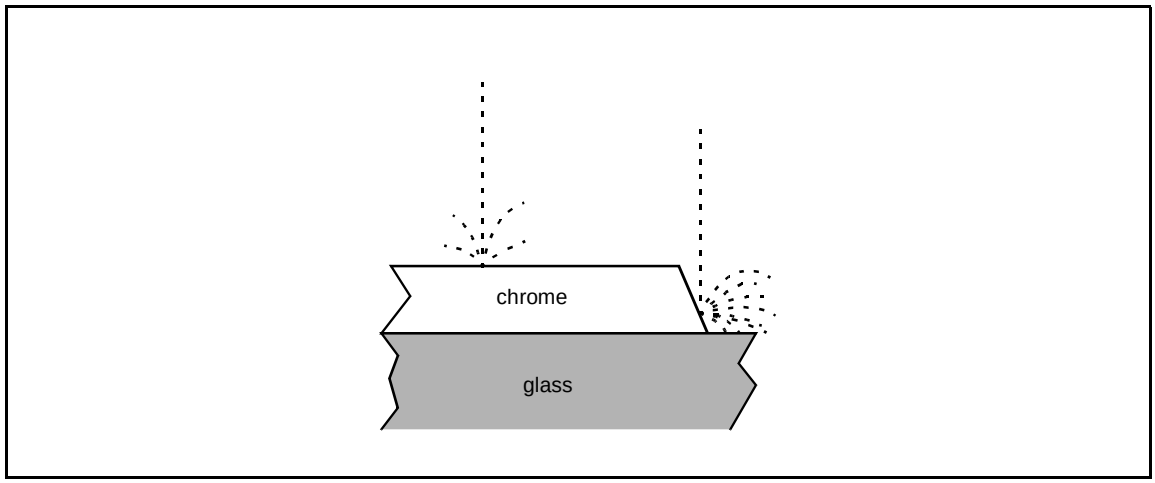



**Figure 24. Edges Etch Faster than Flat Surfaces.**

Various scanning arrangements have been devised to minimize the riverbed effect, but the best results are obtained through the dose-reduction allowed by the use of the chrome-GAE process described earlier.

**Gallium Removal** The implantation of gallium ions in the quartz substrate in the course of chrome-removal is problematic because the presence of the gallium reduces the transmission of short wave length light by the quartz and it therefore compromises the effectiveness of the repair process. However, because xenon difluoride ($XeF_2$) vapor is highly reactive with quartz, it can be used in conjunction with a relatively light ion dose to remove the implanted layer of quartz without resulting in further implantation. The xenon difluoride used for gallium removal is stored in its chemical cabinet at room temperature.